NPS-63-88-005

NAVAL POSTGRADUATE SCHOOL

Monterey, California

ONR TROPICAL CYCLONE MOTION
RESEARCH INITIATIVE:
MID-YEAR REVIEW, DISCUSSION
AND WORKING GROUP REPORTS

RUSSELL L. ELSBERRY

SEPTEMBER 1988

Interim Report for Period
October 1987 - September 1988

Approved for public release; distribution unlimited

Prepared for:
Chief of Naval Research (Code 1122MM)
gton, VA 22217

Naval Postgraduate School
Monterey, California 93943

Admiral R. Austin
Superintendent

H. Shull
Provost

The work reported herein was in support of the Accelerated Research Initiative on Tropical Cyclone Motion of the Office of Naval Research (Marine Meteorology). The Chief of Naval Research provided some travel funds to support the attendance of a few participants. Funding for preparation of the report was provided by the Naval Postgraduate School.

This report was prepared by:

Unclassified

RITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

EPORT SECURITY CLASSIFICATION Unclassified	1b RESTRICTIVE MARKINGS
ECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited
ECLASSIFICATION / DOWNGRADING SCHEDULE	
RFORMING ORGANIZATION REPORT NUMBER(S) PS-63-88-005	5 MONITORING ORGANIZATION REPORT NUMBER(S) NPS-63-88-005
AME OF PERFORMING ORGANIZATION val Postgraduate School	6b OFFICE SYMBOL (If applicable) 63
7a NAME OF MONITORING ORGANIZATION Office of Naval Research Marine Meteorology Program	
DDRESS (City, State, and ZIP Code) onterey, CA 93943-5000	7b ADDRESS (City, State, and ZIP Code) 800 N. Quincy Arlinton, Virginia 222]7
AME OF FUNDING/SPONSORING ORGANIZATION val Postgraduate School	8b OFFICE SYMBOL (If applicable)
9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER O&MN, Direct funding	
DDRESS (City, State, and ZIP Code) terey,CA 93943-5000	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO · PROJECT NO · TASK NO · WORK UNIT ACCESSION NO

ITLE (Include Security Classification) ONR Tropical Cyclone Research Initiative: Mid-year Review, Discussion and Working Group Reports

ERSONAL AUTHOR(S) Russell L. Elsberry

TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Interim	FROM 10/87 TO 12/88	1988 September	

UPPLEMENTARY NOTATION

COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Tropical cyclone motion Tropical meteorology Typhoon motion

BSTRACT (Continue on reverse if necessary and identify by block number)

The Office of Naval Research Tropical Cyclone Motion initiative is a ve-year program to improve basic understanding of tropical cyclone motion. 29 June - 1 July 1988, a meeting was held near Brisbane, Australia to:) Review recent research activities; (ii) Discuss issues and plan future search; (iii) Discuss the hypotheses that might be explored in a field periment in the western North Pacific region during summer 1990; and (iv) rm working groups to begin planning for the field experiments. Each of ese topics will be briefly discussed to indicate the progress and plans of e initiative.

STRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION Unclassified	
NAME OF RESPONSIBLE INDIVIDUAL Russell L. Elsberry	22b TELEPHONE (Include Area Code) (408) 646-2373	22c OFFICE SYMBOL Code 63Es

ORM 1473, 84 MAR 83 APR edition may be used until exhausted
All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

Table of Contents

Abstract

The Office of Naval Research Tropical Cyclone Motion initiative is a five-year program to improve basic understanding of tropical cyclone motion. On 29 June - 1 July 1988, a meeting was held near Brisbane, Australia to: (i) Review recent research activities; (ii) Discuss issues and plan future research; (iii) Discuss the hypotheses that might be explored in a field experiment in the western North Pacific region during summer 1990; and (iv) Form working groups to begin planning for the field experiments. Each of these topics will be briefly discussed to indicate the progress and plans of the initiative.

1. Introduction

A five-year basic research program to improve understanding of tropical cyclone motion began 1 October 1986 under the sponsorship of the Office of Naval Research Marine Meteorology Program (R. F. Abbey, Jr., Program Manager). This program involves theoretical studies, analysis of existing observational data, and a field experiment in the western North Pacific region during summer 1990. A series of workshop reports (Elsberry, 1986; 1987a; 1987b; 1988) describe respectively: the planning of theoretical studies; possible observing systems for tropical cyclone studies; a reassessment of the program in view of elimination of aircraft reconnaissance in the western North Pacific during 1987; and review the first-year progress and tentative hypotheses.

A workshop was held on 29 June - 1 July 1988 to review the progress on the initiative. A list of attendees is given in Appendix A. We continue to benefit by the participation of cooperating agencies, such as the Hurricane Research Division (HRD) of the National Oceanic and Atmospheric Administration (NOAA). Because the workshop was held near Brisbane, Australia in conjunction with the International Conference on Tropical Meteorology, a number of international scientists could participate in the discussions.

The agenda for the workshop is provided in Appendix B. The objectives of the workshop were four-fold: (i) Present reports of recent progress; (ii) Discuss the status of the issues being addressed and identify future areas of research; (iii) Discuss the hypotheses for the 1990 field experiment; and (iv) Form working groups to begin planning for the field experiment.

R. Abbey of ONR opened the meeting by briefly reviewing the status of the project. The amount of funding to continue the research studies and carry out the field experiment is very limited. Careful planning will be necessary to accomplish the goals of the initiative.

The first day and part of the second day of the workshop were devoted to progress reports by ONR contractors and by participants from cooperating agencies (see agenda in Appendix B). Although some of this work is nearing publication, other portions are recent results that may change with further investigation and analysis. Consequently, no attempt is made to describe these presentations in detail. Many of the presentors have provided summaries that are included in Appendix C.

2. Discussions of issues

As in previous workshops, discussion leaders and rapporteurs were appointed to focus on tropical cyclone motion issues for which progress has been achieved, the areas where differences are evident and future research requirements. Discussion sessions were organized into observational (G. Holland), theoretical (H. Willoughby) and numerical (W. Schubert) topics. The rapporteurs for these sessions were J. Chan, D. Stevens and R. Smith, respectively. As the discussions ranged across the observational, theoretical and numerical approaches, the presentation here will be according to issues rather than by approaches.

a. Decomposition of the flow

This issue was a central topic in the first planning meeting on the theory of tropical cyclone motion held in July 1986 (Elsberry, 1986). The approach suggested at that meeting was to separate the flow into a symmetric vortex, a spatially uniform environmental flow and an asymmetric component that contained the components resulting from interactions between the symmetric vortex, the earth vorticity field and the environmental flow. For this approach to be useful, a well-established and justifiable methodology must be agreed upon for calculating and analyzing the environmental flow. For example, is it more fruitful to consider the asymmetries to be part of the internal vortex or to be part of the external environment? One participant questioned if it might be misleading to decompose the flow components in a complex, nonlinear phenomenon such as the tropical cyclone.

R. Smith reopened this discussion by proposing the use of the Kasahara and Platzman (1963) method of separating the vortex and the environment. That is, the structure of the vortex is kept constant during the diagnosis of numerical model integrations. The difference between the total flow and this time-invariant vortex is then defined as the interaction. Although this method provides an unambiguous separation for modeling studies, the application to observations could mask important processes. As the tropical cyclone structure changes throughout its life cycle, an arbitrary decision would be required in selecting the vortex structure at a single time as being representative of all times. Modeling studies by Fiorino (1987), Shapiro, Evans and Holland, Holland and Hodur (Appendix C) demonstrate that the structure of the vortex evolves markedly with time. If the vortex structure had been held fixed in time during analyses of these simulations, the derived asymmetric circulations would have included some of the symmetric vortex circulation change. In summary, keeping the vortex constant in the decomposition of the flow will obscure the description of the interaction between the vortex and the environment.

Although the consensus of the workshop participants was to retain the previously agreed method of decomposition with a time-dependent vortex, problems also arise with this method. It is not always possible to distinguish cyclone vorticity from the environmental vorticity, especially in a monsoon trough environment. The question of how to define the boundary of the vortex still remains (see later discussion). Vortices that have been specified in recent model simulations have been somewhat unrealistic, i.e., the relative vorticity becomes negative at too small a radius.

Willoughby suggested that the vortex boundary be at the radius at which the area-integrated relative angular momentum (RAM) is zero. This may also be unrealistic as western North Pacific typhoons have cyclonic circulations at low levels that extend beyond 15^{o} lat. radius (Frank, 1977). Furthermore, application to a three-dimensional vortex, in which the RAM would be equal to zero at different radii for various pressure levels, is not obvious.

Another difficulty in the decomposition procedure is associated with the definition of the environmental flow from observations. The numerical and analytical model studies have well-defined uniform flows or smoothly varying shears. In the observational studies, a method must be found to remove the tropical cyclone scale circulation that does not also eliminate environmental features such as narrow ridges, etc., that have similar horizontal scales.

Some disagreements have arisen in the definition and dynamical meaning of smaller (approximately radius of maximum wind speed) scale gyres. These smaller gyres, termed alpha-gyres in the previous workshop (Elsberry, 1988), are strongly affected by the definition of the storm center. According to Fiorino and Elsberry (1988), the alpha-gyre circulation is actually reversed if the center is defined in terms of the maximum vorticity rather than the minimum stream function in their non-divergent barotropic simulations. Selecting the storm center halfway between these two alternatives almost eliminated the alpha-gyre circulation. Because of the arbitrariness of these definitions, Fiorino and Elsberry concluded that the alpha-gyres probably have little to do with the large-scale motion of the tropical cyclone vortex. Williams and Peng (see Appendix C) have recently studied the structure and effects of inner gyres similar to the alpha-gyres.

Observational studies at the Hurricane Research Division in Miami, Florida indicate that the alpha-gyres can not always be eliminated by a single choice of the coordinate system origin (F. Marks, P. Black and H. Willoughby, personal communication). The problem is complicated in observational analyses because of the vertical shear in the environment and the vertical tilt of the center position. These observationalists believe the alpha-gyres may have an important role in inner storm motion.

Recommendations: The focus in the discussion of decomposition of the flow needs to be shifted from decomposition procedure to producing a better understanding of the limitations and implications of our agreed three-component system with time-dependent vortex structure. Second, further observational studies are required to demonstrate that a significant contribution to the total storm motion is associated with alpha-scale gyre circulations.

b. Structure and orientation of the beta-gyres

Documentation of the existence of large (similar scale as the cyclone circulation) gyres in the asymmetric circulation around tropical cyclones has been one of the early achievements in this ONR research initiative. The role of these gyres has been well-illustrated by the numerical simulations of Fiorino (1987). In his nondivergent barotropic model with no uniform flow on a beta-plane, the cyclonic (west of center) and anticyclonic (east of center) gyres develop very rapidly due to the linear (v) forcing. The flow between the gyres is the primary factor in the beta-induced motion of the vortex. DeMaria (1985) and Fiorino demonstrate that it is the strength of the <u>outer</u> (say beyond 300 km) winds rather than the inner winds that determines the speed of translation. The swirling motion of the vortex tends to rotate cyclonically the inner regions of these gyres, and thus the direction of the vortex motion. Consequently, the structure of the vortex, especially in the outer regions, is important for tropical cyclone motion associated with the beta-effect.

An observational study by Chan (1986) of a very large typhoon in a weak steering flow reveals similar gyres that rotate such that the storm motion appears to be oriented with the flow between gyres. Analyses of the Australian Monsoon Experiment (AMEX) cases by Holland also reveal gyre circulations similar to Fiorino's simulations, but the gyres seem to maintain an east-west orientation. Holland and Hodur (see Appendix C) also have detected gyre circulations in three-dimensional bogus vortex spinups that are used in the Advanced Tropical Cyclone Model (ATCM) at the Naval Environmental Prediction Research Facility in Monterey, California. The gyres in these simulations appear to rotate cyclonically and dissipate in time, with new gyres forming in the east-west direction. An important finding is that the gyres are present only below 300 mb. The gyres are either not present, or are masked by other asymmetries in the outflow regime.

Gray (see Appendix C) presented an extensive set of composites of rawinsonde observations of tropical cyclones stratified in various ways. Gyre-like circulations are clearly evident. Furthermore, the orientation of the flow between the gyres seems to be along the storm track for different storm motion stratifications.

Since the early studies of these gyres have been with models that only included the beta-effect, it seemed quite reasonable to call them beta-gyres. However, any asymmetry imposed on the vortex (such as asymmetrical frictional effects or convective release of latent heat) will tend to create similar wave number one circulations. Positive identification of the beta-related gyres requires a particular orientation relative to the earth's vorticity gradient, or more generally the gradient of environmental vorticity.

<u>Recommendations</u>: The goal is to isolate the special characteristics of the large-scale, wave number one gyres that are associated with the earth's vorticity gradient, the relative vorticity gradient, asymmetric convection, frictional effects, vertical shear effects, etc. Particular focus should be on the conditions leading to recurvature, such as during interaction with a midlatitude trough. Future numerical, case study or composite analyses should attempt to distinguish between the various physical mechanisms that generate the beta-gyres. If physical processes other than the environmental vorticity gradients contribute significantly to these beta-gyres, a more suitable designator should be used to avoid confusion.

c. Motion due to propagation

In the numerical simulations (Fiorino, 1987) of the beta-effect in a no-flow environment, the beta-gyres discussed in Section 2b lead to an advection of the vortex core by the flow between the gyres. In this model result, the motion of the vortex may be thought of as a <u>propagation</u> relative to the (zero) steering flow. In nature, it is not easy to calculate the difference between motion due to advection by the steering current and the storm propagation. As indicated in Section 2b, several physical effects besides the beta-effect may contribute to this propagation vector.

A number of studies based on composited rawinsonde sets have verified that the storm motion deviates from the steering flow (e.g., George and Gray, 1976; Chan and Gray, 1982; Holland, 1984). Steering flow in these studies is defined as the azimuthal average of the winds within some annulus around the center, e.g., 1°-3° lat., 3°-5° lat., 5°-7° lat., etc. These steering flows are defined at single pressure levels or averaged over various depths. The deviation of the storm motion vector of each steering flow also could be defined as a propagation. Unfortunately, as many values of propagation vectors exist as definitions of the steering flow.

If perfect wind observations with adequate horizontal resolution existed near the center, a volume-weighted average could be calculated to define the steering flow. In a barotropic numerical simulation such as Fiorino (1987), the average can be calculated rather accurately. Fiorino found that the flow averaged over the inner 300 km radius was within ~0.3 m/s of the storm motion. As indicated above, the entire vortex motion in this no environmental flow simulation may be defined as propagation.

The question in observational studies is: over what areal domain and vertical layer thickness should the calculation of the steering flow be made? Factors such as the rawinsonde wind accuracy, the distribution of the observations within the areal domain and the number of observations to obtain stable mean estimates must be considered. The number of rawinsonde observations near the center in the above composite studies is relatively small because of the difficulty of launching balloons in such high surface wind conditions. Gray (see Appendix C) finds that the rawinsonde observations averaged within the 1^{o}-3^{o} lat. annulus result in a steering flow that is faster and to the right of the storm motion. Because of the factors listed above, some caution must be advised in attributing this result to physical processes only.

Holland proposed defining the average of the wind observations within the 5^{o}-7^{o} lat. annulus over the 850-300 mb layer as the standard steering flow. Any departure of the storm motion vector from this steering flow definition would be considered as propagation. The choice of the 5^{o}-7^{o} lat. band would be consistent with the Chan and Gray (1982) and Holland (1984) studies. Generally, sufficient observations are available in this region to define the flow. The centers of the beta-gyres in the Fiorino (1987) simulations also were generally in this radial band, so the flow between the gyres would not be added into the steering flow. If a much larger than the 5°-7° radial band is selected, the average flow could be biased by the wind shear in the environment and by the reversed flow in the outer region of the beta-gyres. Therefore, the selection of the 5°-7° lat. annulus is a reasonable compromise for the definition of the steering flow.

Recommendations: Steering flow calculations should be standardized as the average of wind observations within the 5°-7° lat. annulus and over the 850-300 mb layer. Motion due to propagation may then defined as the departure of the storm motion from this standard steering flow. Observational and modeling studies should evaluate the suitability of this standard definition relative to larger or smaller horizontal and vertical domains. Special attention should be given to the suitability for large versus small storms, different environmental flow regimes, seasonality, etc.

d. Barotropic representations of tropical cyclone motion

Much of the analytical theory and the numerical modelling has assumed barotropic flows. Furthermore, a no-flow environment has been assumed in many of these studies, which are aimed at understanding the storm motion departures from steering. DeMaria (1985) has described the effects of an environment flow with sinusoidal variations. Chan and Williams (see Appendix C) are examining the effects of shear. When a linear cyclonic (anticyclonic) shear is imposed in a nondivergent barotropic model, the track of the vortex is more toward the west (north) than the beta-effect with no uniform flow. Evans and Holland (see Appendix C) are also examining more realistic environmental conditions with the shallow water equation set. They are placing the tropical cyclone in various locations relative to an idealized representation of the subtropical ridge and monsoon trough. They find that the beta-gyres can reinforce the subtropical high pressure in special cases and that the relative vorticity gradient can affect storm motion. Smith and Ulrich (see Appendix C) have begun modelling the interaction of a tropical vortex with a Rossby wave. Each of these studies with more realistic environments should advance our understanding of the conditions associated with recurvature.

As described above, this project has documented the character of the beta-gyres and their relationship to vortex motion. However, we need to examine the extent to which these results based on barotropic models can be applied to vertically varying modes and to real-data cases.

One of the potential applications of the beta-gyres is to improve the initialization of numerical track prediction models. Clearly, the initial conditions in a <u>barotropic</u> prediction model should include the asymmetric circulation associated with the beta-gyres to ensure that the initial track motion in the model prediction has the correct direction and speed. It is unclear whether the beta-gyres in the <u>baroclinic</u> models differ significantly from the barotropic model representations (see Section 2b).

L. Shapiro (see Appendix C) suggests that the most conservative bogus vortex specification in a numerical model would be a truly "isolated" vortex. A vortex with zero relative angular momentum would not generate any Rossby waves, and thus is isolated. Other vortex specifications will initiate Rossby waves that may have an incorrect amplitude or phase. Thus, Shapiro is proposing that no Rossby waves are better than incorrect waves. The counter argument is that vortices in nature do not have zero RAM and do generate Rossby waves that are part of the solution at the initial time and that could have significant effects. Further study of the initialization problem is required.

Part of the justification for L. Shapiro's suggestion is that the tangential wind profiles in nondivergent barotropic models tend toward a zero RAM profile, which Fiorino (1987) labels as a beta-neutral profile. However, real tropical cyclones do not have zero RAM profiles in the lower troposphere. Furthermore, Holland does not find a tendency to develop a zero-RAM profile in the three-dimensional spinups with the ATCM. This unrealistic tendency toward a zero-RAM profile in the nondivergent, barotropic models seems to be due to the absence of a secondary circulation.

Recommendations: A better understanding of the extent to which barotropic processes contribute to tropical cyclone motion is needed. Attempts to apply the beta-gyre structure to the initial conditions for dynamical track prediction models should be continued. A better understanding of the three-dimensional tropical cyclone vortex structure and structure change is necessary for motion understanding.

e. Baroclinic processes in tropical cyclone motion

A hierarchy of dynamical model for motion studies from simplest to most complex might be: (i) nondivergent barotropic; (ii) shallow water; (iii) two- or three-level baroclinic with simple physics; (iv) multi-level baroclinic with complete physical process representations; and (v) global domain, general circulation models with complete physics. The primary distinction between the last two categories is that category (iv) will have a limited horizontal domain, generally with higher resolution than the global models. However, present and proposed global models at various numerical weather prediction centers (or research groups such as T. N. Krishnamurti at Florida State University) have horizontal resolutions that are better than some operational dynamical track prediction models. The advantage of the global model relative to the limited-area model is that it avoids the specification of the interface boundary conditions, which is the primary source of forecast error in most limited-area models.

The operational numerical weather centers have recently become concerned with tropical cyclones because their global models now have horizontal grids that resolve some aspects of tropical cyclones. Furthermore, these tropical cyclone-like features may persist long enough to move into the midlatitudes on the time scale of the medium-range predictions.

The transition from a single-layer barotropic or shallow water model to a multi-level model introduces a fundamental problem. That is, the vertical coupling between the layers in a tropical cyclone is via the latent heat release in clouds. Thus, the vertical motion, divergence-convergence and other physical processes must be represented in baroclinic models. For example, frictional processes become important both as a mechanism for dissipating energy as well as inducing vertical motion, moisture flux or other energy fluxes, etc. Incorrect representations of these physical processes will lead to incorrect vertical coupling between the layers, which will affect the vorticity tendencies associated with the motion. Consequently, the degree of complexity in baroclinic model studies of tropical cyclone motion is much greater than in barotropic models.

Initially, a first internal mode might be included with only two or three levels to study baroclinic effects on tropical cyclone motion. A key question then is how to handle the vertical coupling between the two layers. Since the representation of the physical processes is crucial to the coupling, the extension to baroclinic models will require some innovative and careful study.

The other approach is to go to the complex baroclinic models with complete physics. Since the computational resources are limited, some trade-offs are necessary between vertical and horizontal resolution, between parameterizations versus explicit representations of physical processes, between dynamical versus physical processes and between initialization time versus forecast time for operational models. Sophisticated global research models such as the Florida State University model have produced some very commendable predictions of tropical cyclone tracks. However, it is very difficult to establish for only a few cases whether this success is due to special initial condition preparations, to enhanced horizontal or vertical resolutions, to improved physical representations or perhaps to fortuitous situations. To transfer these track prediction successes to operational models that have limited resources and strict time schedules, a better understanding is required of the key features in the model (or the data).

Observational studies by Gray (see Appendix C) indicate that the most significant differences in environmental fields between recurving and non-recurving cases are found in the upper troposphere. Gray finds differences in the import of angular momentum between pre-recurvature and post-recurvature cases. The low-level inflow is from the north in both cases. In the pre-recurvature case, the compensating outflow is to the south, so a net import of earth angular momentum occurs. In the post-recurvature case, no net torque is added because the compensating outflow is northward at the same latitude as the inflow. How these differences might change the vortex structure and the motion deviations from steering need to be investigated.

Recommendations: The progress in understanding tropical cyclone motion from barotropic models must be extended to baroclinic models if direct applications to real situations are to be made. Studies with simple two-layer models should include sensitivity studies that illustrate the impact of the physical processes in more complex three-dimensional models. Modeling and observational studies should address baroclinic effects such as vertical shear in the environment, convection, friction and other physical processes.

3. Refining the hypotheses

The report of the previous workshop (Elsberry, 1988) listed five tentative scientific hypotheses that might be examined during the field experiment phase:

(i) The beta gyres arising from Rossby mode dispersion of the cyclone in a gradient of earth vorticity can reach sufficient amplitude to modify the subtropical ridge.

Thermal and indirect circulation effects associated with the tropical cyclone outflow jets can produce a westward extension of the mid- to lower-level subtropical ridge and cause a continued westward motion of the cyclone.

(ii) The approach of an environmental trough may excite barotropically unstable azimuthal waves in the tropical cyclone outflow layer that extend downward into the lower troposphere and affect the cyclone motion.

(iii) Tropical cyclone turning motion, or the absence of any turns in the immediate future, may be monitored by accurate representations of the large-scale vorticity patterns in the environment of the cyclone.

(iv) Significant tropical cyclone track and direction changes (such as steps) can occur during periods of direct or indirect (e.g., induced monsoon surges) interaction with TUTT cells.

(v) Given adequate four-dimensional observations to define the initial conditions, the 24-hour track prediction error should not exceed five grid points of the model resolution.

During the discussions, it became apparent that some of the initial hypotheses could be combined, and that one should be replaced. Accordingly, there are currently three hypotheses listed as A-C below. Hypothesis A is a combination of initial hypotheses (i) and (iii), B is a combination of (ii) and (iv), and C is a new hypothesis proposed by H. Willoughby. Initial hypothesis (v) was deleted after general agreement that it could not be adequately addressed with the proposed western North Pacific field experiment. Some of the points that led to the refinement of the hypotheses are discussed below. Much of this description in this and the following section was prepared by W. Frank, who served as rapporteur for this discussion.

HYPOTHESIS A

INTERACTIONS BETWEEN LARGE INTENSE TROPICAL CYCLONES AND THE SUBTROPICAL RIDGE WILL MODIFY BOTH CIRCULATIONS AND CAUSE SIGNIFICANT DEPARTURES IN THE TROPICAL CYCLONE TRACK COMPARED TO AN UNMODIFIED RIDGE-CYCLONE SITUATION.

Two specific modes of interaction were discussed in Elsberry (1988). One is the generation of beta-gyres arising from Rossby mode dispersion of the cyclone in a gradient of absolute vorticity. These gyres are hypothesized to be strong enough to alter the circulation of the subtropical ridge and to create a steering current near the storm center that differs significantly from the flow of the unmodified ridge. The second mode of interaction is a westward extension of the subtropical ridge in the lower to middle troposphere, caused by thermal and indirect circulation effects of the outflow jets, that tends to move the storm westward and inhibit recurvature. Recent observational evidence has indicated that storms tend to move along nodes or channels in the large-scale vorticity field, which is in turn affected by the storm circulation. It is proposed that improvements in storm track forecasting may result if data are available to monitor the vorticity fields with sufficient accuracy. The planned field experiment during Summer 1990 will provide such data.

HYPOTHESIS B

SIGNIFICANT TURNS IN THE TROPICAL CYCLONE TRACK OCCUR WHEN THE INTERACTION WITH TRANSIENT SYNOPTIC-SCALE FEATURES, SUCH AS MIDLATITUDE TROUGHS OR TUTT CELLS, CAUSES A RESPONSE THAT EXTENDS THE EFFECTS OVER A DEEP LAYER.

As discussed in Elsberry (1988), interactions with approaching westerly troughs may excite a type of normal mode response in the upper levels that propagates downward and modifies the flow in lower levels. TUTT cells may affect storm tracks directly by altering the low-level flow, or by indirectly altering the flow surrounding the tropical cyclone through their effects on storm structure.

HYPOTHESIS C

A LIMITED SET OF PROPAGATION VECTORS, WHICH ARE THE DEPARTURES OF THE STORM MOTION FROM A SPECIFICALLY DEFINED STEERING FLOW, MAY BE DEFINED FOR PARTICULAR CYCLONE CHARACTERISTICS AND ENVIRONMENTAL FLOW CONFIGURATIONS.

The motion of a tropical cyclone may be defined as the sum of advection by the environmental steering flow plus a propagation vector. For example, it was proposed in Section 2c that the steering can be <u>defined</u> as the vector average wind within the 5°-7° radial annulus around the cyclone center. Since advective steering seems to be the dominant process in tropical cyclone motion, the optimum situation would be that a <u>single</u> propagation vector would apply in all situations. If not, it is hypothesized that only a limited set of average propagations vectors will be necessary for stratifications by cyclone characteristics (such as size) and/or environmental flow conditions (such as environmental shears or vorticity gradients).

4. Discussion of hypotheses

A key aspect in the design of the field experiment is the minimum network of observations to test the proposed hypotheses. At this stage in the planning, both the hypotheses and the components of the observational network are still somewhat tentative.

For purposes of continuing the discussion of the hypotheses, a strawman network of observation sites was presented (Fig. 1). The components of the network include:

(i) Existing rawindsonde stations. The stations shown in Fig. 1 have been verified with the meteorological services in the Asian area.

(ii) Additional rawindsonde stations. Approximately ten additional stations may be added during the field experiments. Most of the observations would be made with portable rawindsonde systems that have recently become available. The locations shown in Fig. 1 are very tentative, and are subject to negotiation of agreements with the host country or to shifts necessary to accomplish scientific objectives.

(iii) Existing radar wind profilers. A new technology for almost continuously observing wind profiles throughout the lower troposphere with radar wind profilers has recently become available (Peterson, 1987). Although three profilers exist within the region of interest (Fig.1), none of the observations have been made available to operational weather analysis centers.

(iv) Additional radar wind profilers. It is expected that at least two more wind profilers will be available during the experiment. In the strawman network, these profilers are placed along 25°N to monitor the subtropical ridge circulation. These locations are subject to successful negotiations, or shifts to satisfy other scientific objectives.

(v) Ships with rawindsonde capability. Large gaps are found in the strawman network of existing and proposed rawindsonde and wind profiler sites. Since no island or land sites are available, these gaps must be filled by ships that have the capability to launch rawindsondes. The proposed arrangement of ships in Fig. 1 is intended to fill the data gaps by positions along east-west and north-south sections. The sources of these ships are uncertain at this time, although preliminary inquiries have been made to several Asian nations. For example, I. Sitnikov of the USSR has indicated that perhaps four ships from that country will be studying tropical cyclones in the western North Pacific during summer 1990. It is possible that some type of cooperation with the USA experiment might be arranged.

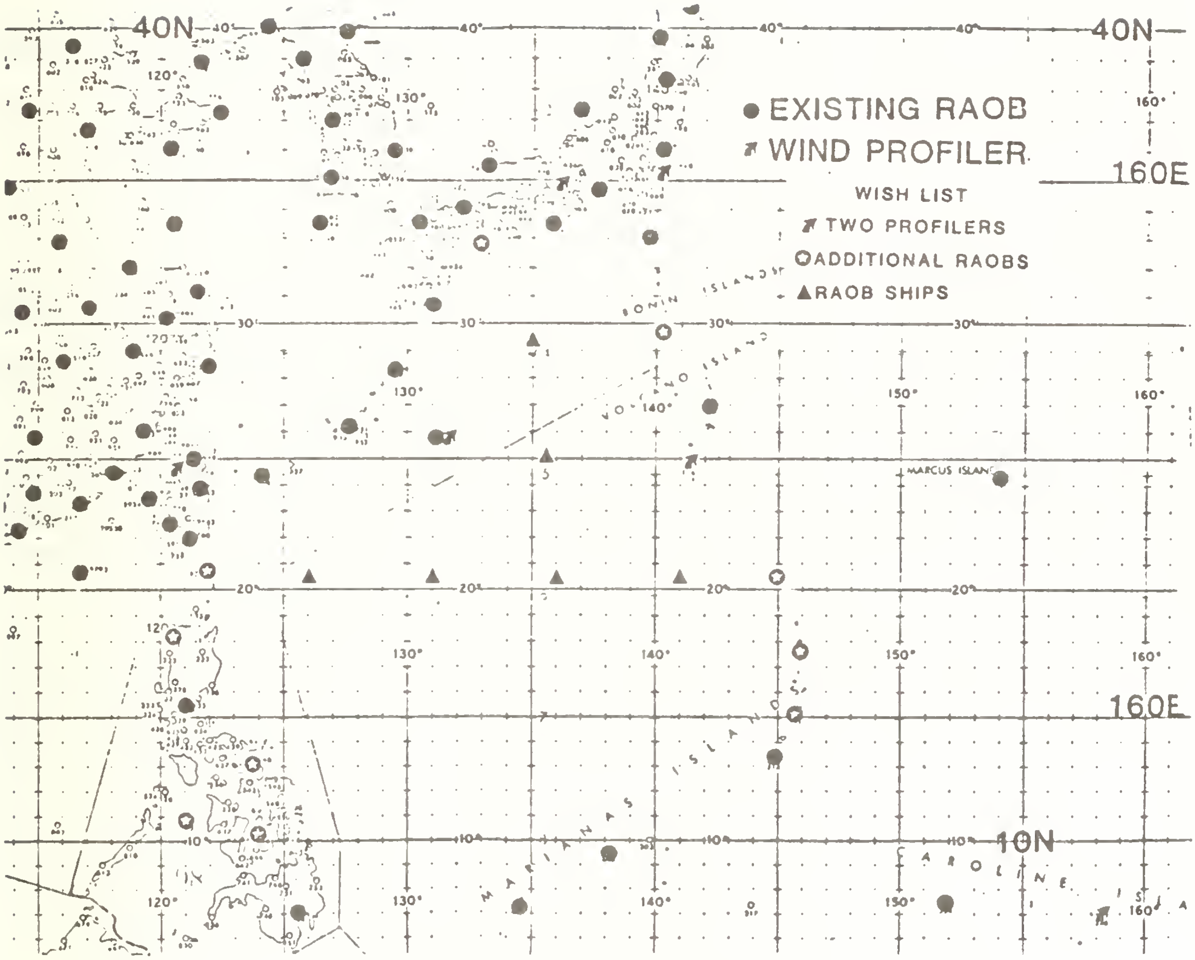


Fig. 1 Proposed observational network for the field experiment during Summer 1990, which includes existing rawindsondes (solid dots), additional rawindsondes (dots with enclosed stars), radar wind profilers (curved arrows) and ships with rawindsonde capability (triangles).

Some other proposed components in the field program are not indicated in the strawman network: satellite data; an enhanced surface observing network of automatic stations and drifting buoys; and presently available aircraft reports and proposed research aircraft. These components will be discussed later in the Working Group reports.

Given the strawman network in Fig. 1, the participants discussed the hypotheses presented in Section 3. Some of the key points from those discussions follow.

HYPOTHESIS A

The primary questions were whether the beta gyres were large and strong enough to affect the large-scale flow and whether the field program observational network will be adequate to resolve them. Regarding the latter, there was considerable concern that the array south of the line of profiler stations was inadequate to resolve the gyre structure, the axisymmetric storm structure, or the large-scale gradients of absolute vorticity. It was agreed that strong emphasis should be placed on trying to obtain ships for observations along 20°N and that it would be highly desirable to locate at least one ship in the southern portion of the Philippine Sea to aid in computations of vorticity. It also was suggested that a numerical model could be used to interpolate storm and gyre structure from the observations, and thereby facilitate separation of these features from the large-scale flow.

There was some discussion of how the theory of gyre effects relates to the Gray hypothesis of inner core response due to asymmetrical flow-through (in north, up, out south). Further study and a concise formulation of the latter hypothesis were suggested.

HYPOTHESIS B

Interactions between a trough or TUTT cell and a tropical cyclone result in significant asymmetries in the circulation of the storm. This in turn makes it difficult to separate the symmetric storm from the large-scale circulation. As with Hypothesis A, much of the discussion centered on the need to ensure that sufficient data are available around the storm to resolve both the symmetric storm and the evolving asymmetries. The need for more data to the south of the array was noted. Although satellite winds in the upper troposphere should be useful, cloud-drift winds are often scarce ahead of a moving storm due to the tendency for subsidence there.

Existing data sets should be adequate to provide climatological guidance on the preferred geographical locations of cyclone outflow jets. Gray suggested examination of 3-4 years of European Center for Medium-range Weather Forecasts maps to document the locations of these jets during the time period proposed for the field program.

The interactions between the TUTT and tropical cyclones appear to be related to the depth of the TUTT. Some storms change direction because of these interactions, while in other cases the TUTT retreats in advance of the storm. Also, the interactions seem to be related to the phase relationship between the TUTT and mid-latitude troughs. Current thinking is that TUTT-storm interactions are stronger when the TUTT extends well downward into the middle levels, but existing data sets are inadequate to document TUTT structure, or even the location, to the accuracy needed to analyze this hypothesis. It was noted that the proposed ship stations will probably be essential to resolve the vertical structure of the TUTT due to its expected location over the Philippine Sea.

HYPOTHESIS C

The question was raised as to whether this hypothesis could be investigated without steering flow information directly over and around the storm center. This would be a problem if aircraft are not available. It was suggested that the flow near the center could be parameterized. One method of exploring this hypothesis would be to look for predicted changes in relationships between axisymmetric band averages. That is, the model predictions describe the structure of the wave number one perturbations that tend to propagate the tropical cyclone. Knowing what the structure (signal) should be will assist in the analysis of the observations.

In summary, the above hypotheses could be tested for properly placed tropical cyclones within the strawman observational network in Fig. 1, except that a better representation of the southern branch of the circulation is highly desirable. These aspects will need to be considered as planning for the field experiment proceeds. Additionally, hypotheses will be explored further with available observational data sets and numerical modelling. The result will be more specific, testable hypotheses.

5. Working group formation

One of the objectives of this workshop was to begin exploring the possible observational systems for the 1990 field experiment. Whereas some resources such as the existing rawinsonde network in Fig. 1 are more or less fixed, the number and locations of the additional rawinsonde sites are not. A justification and a priority for each additional site must be established to assist in decisions regarding the optimum network given that limited finances are available.

Provisional working groups were formed to begin addressing these possible components of the field experiment. The participants in the working groups are listed in Table 1. Preliminary reports from the groups follow. More detailed studies will be performed prior to the next workshop in May 1989.

Table 1 Participants in the provisional working groups

Wind Profilers	Satellite Observations	Surface Network	Aircraft	Forecasting Support
Frank	Velden	Schroeder	Willoughby	Holland
Lee	Merrill	Wells	Merrill	Chan
Yamasaki	Gray	Smith	Gray	Arafiles
Willoughby	Shapiro	Reeder	Holland	Evans
Stevens			Schroeder	Krishnamurti
			Wells	Carr
			Shapiro	Wang
			Evans	
			Frank	
			Schubert	
			Carr	
			Chan	

6. Profiler Working Group

a. Scientific justification

Six major scientific reasons for incorporating an array of wind profilers into the tropical cyclone motion field program are provided below.

(i) Need for high time resolution of storm-environmental interactions. The hypothesized interactions between tropical storms, their environment, and external systems occur on time scales that are too short to be detected from the traditional once or twice per day rawindsonde ascents. Even the six-hour launch intervals proposed for the field program may not be sufficient to resolve some of the important transient interactions. To document the nature of these interactions, including the evolving structure of the storm environment and the sequencing of events, the high time resolution of the profiler systems will be of considerable value.

(ii) Improved spatial resolution. One profiler is planned for Iwo Jima (see Fig. 1), which does not have a rawinsonde station. By making assumptions of time continuity, it is possible to utilize the high sampling rates of the wind profilers to extrapolate their measurements in space. As a result, the inclusion of the profiler systems will constitute a modest but important improvement in the data density over the experimental domain. A time-height section over 24 h from one of the Pennsylvania State University (PSU) profilers is shown in Fig. 2. To the extent that steady-state conditions prevail,the sequence of data in time can be used to infer conditions downstream of the station for research analysis.

(iii) Resolution of sub-grid scale phenomena. Some of the circulations and processes that are considered important to tropical cyclone structure and motion occur on scales that are too small to be resolved by the primary observational array. By analyzing time-height sections of winds from profilers as the systems advect over the stations, it will be possible to examine quantitatively such phenomena as:

- the structure of upper-level outflow jets;
- horizontal eddy momentum fluxes; and
- gyres in the lower tropospheric flow.

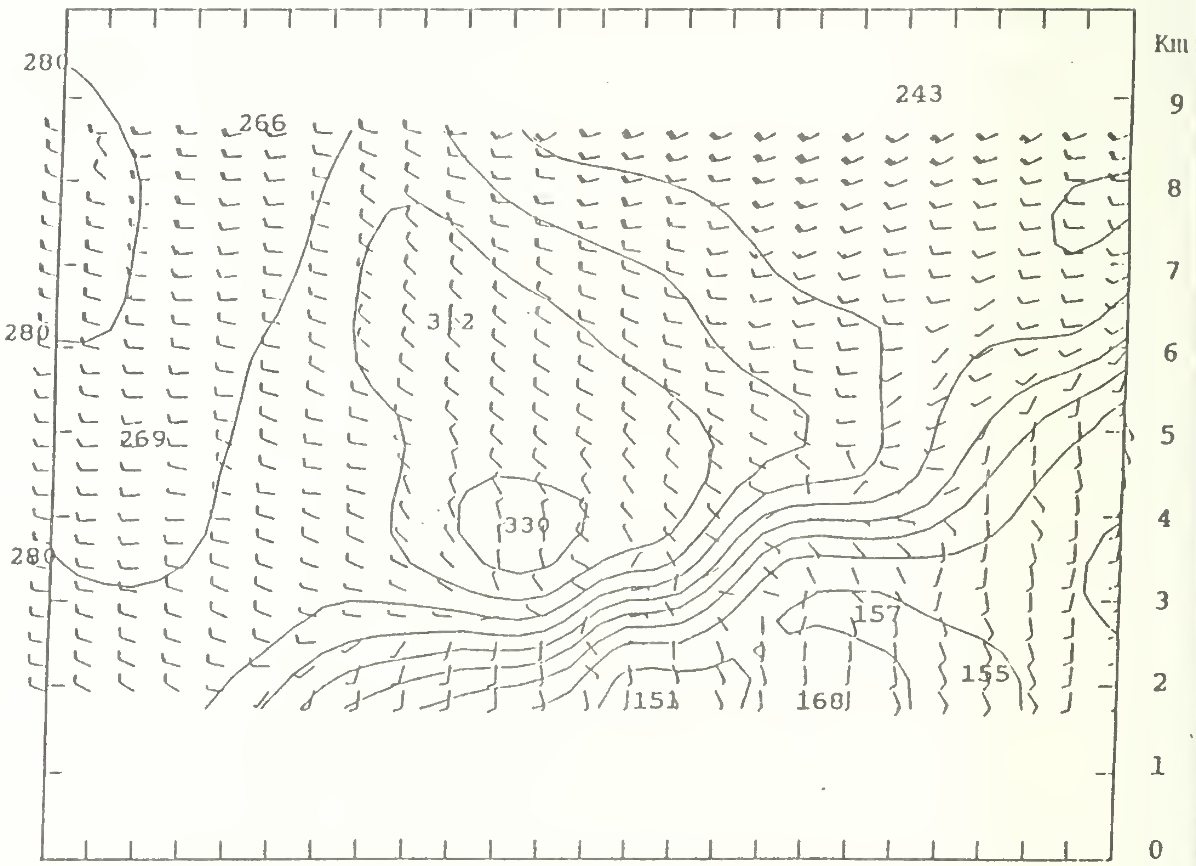


Fig. 2 Time-height section of hourly profiler winds from 12 GMT 18 August (RHS) to 12 GMT 19 August (LHS) 1985. Major ordinate divisions are km, msl. Isolpleths are of wind direction in 20o increments. Vertical resolution set to 300 m.

Compare the resolution of features in Fig. 2 to those in Fig. 3, which contains only the 12 h observations that are available from most rawinsonde networks.

(iv) Real-time guidance during the field program. Using satellite transmission links, it should be possible to have data from most of the profilers available in near real-time at the field experimental headquarters on Guam. This should be a significant aid to the forecasters in making operational decisions such as when to activate special observing procedures at the rawinsonde stations and when and where to deploy aircraft.

(v) Data assimilation techniques. One of the more important research activities relating to wind profilers is the development of methods for 4-dimensional data assimilation for initialization of numerical models. The 1990 field program will provide a unique opportunity to examine this problem with multiple profiler systems operating in a tropical maritime environment.

(vi) Profiler performance in tropical regimes. Although wind profiler systems are becoming more standardized, most systems currently in use have at least some different hardware components. Since the operation of profilers in tropical maritime environments has only been examined from two systems, there are still considerable uncertainties as to their vertical operating ranges,

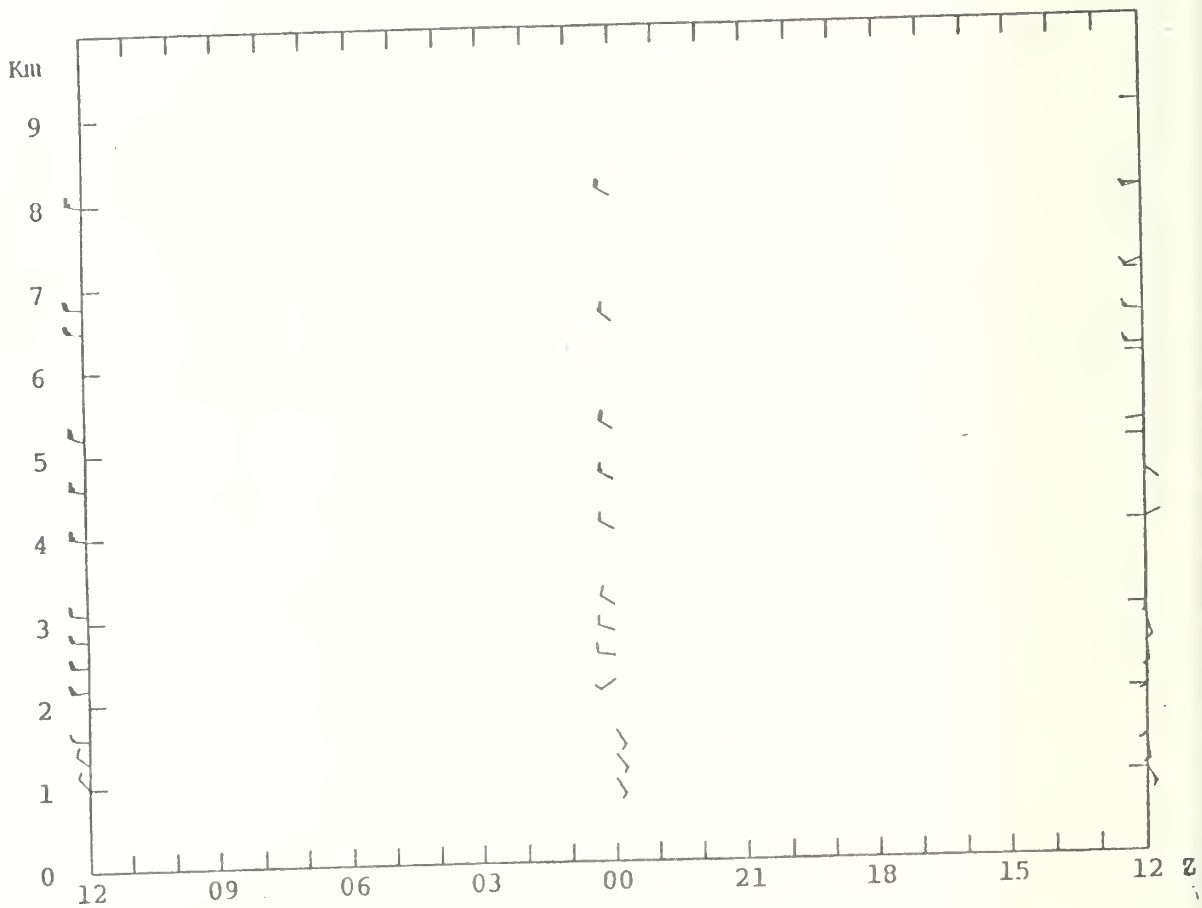


Fig. 3 Conventional wind measurements at 12 GMT 18 Aug (RHS) and 00 and 12 GMT (Center and LHS) 19 Aug 1985 from Pittsburgh, Penn NWS upper air sounding station, the closest to Penn State's Shantytown profiler. Major ordinate divisions are km, msl. No time-height isoplething of speed or direction has been attempted.

accuracies and the effects of heavy tropical rainfall on the signals. This is particularly true of the 405 MHz frequency systems. The field program will deploy a variety of 50 MHz and 405 MHz systems and should increase understanding of profiler performance in moist regimes.

b. Technical aspects of wind profilers

All present wind profiler systems are to some extent idiosyncratic due to differences in the components, and only limited experience has been gained with profiler operation in the moist environment of the tropical oceans. Based on experience with the Pennsylvania State University systems in other locations, the following performance characteristics are expected:

(i) <u>50 MHz</u>. These systems should be able to resolve winds between about 1.3 km Above Ground Level (AGL) and 18.5 km. They are capable of retrieving a three-dimensional wind profile every 90 sec with 300 m vertical resolution below 9 km and 1 km resolution from 9-18.5 km elevation. They can operate in rain unless the precipitation rate reaches a level equivalent to about 35 Dbz of radar reflectivity, which is typical of a strong convective cell of short duration, or a typhoon rainband.

(ii) <u>405 MHz</u>. The PSU 405 MHz system can obtain wind measurements as low as 200 m AGL. In the rather dry environment of Tucson, Arizona, it is currently obtaining winds continually up to 8 km and sometimes as high as 10-11 km. In the tropical maritime environment, one would expect the 405 MHz systems to be effective at higher levels, perhaps to 12 km. These profilers do not operate satisfactorily during rain.

More detailed specifications of the 50 and 405 MHz profilers are listed in Table 2.

c. Availability and costs

There are currently three 50 MHz profilers operating in the experiment region. They are located at Ponape, Taiwan and Kyoto in Japan. It is assumed that these systems will remain in place and will operate throughout the two months of the field program. There may be some costs involved in obtaining and processing the data, particularly in real-time.

A 50 MHz system from PSU will be deployed on an island in the experimental domain. Financial support for this operations should come from the ONR-sponsored University Research Initiative at Pennsylvania State University.

A 405 MHz system has recently been installed at the Meteorological Research Institute in Japan. A possibility exists that this system might be moved to Okinawa for part or all of the field program if funds are available from other sources. Such a move would improve the observations along the subtropical ridge. The profiler working group strongly recommends that MRI be contacted to see if the move to Okinawa is possible.

The U. S. Naval Postgraduate School will deploy their new 405 MHz profiler on an island in the experimental

Table 2 Specifications: Active Remote Sensing Systems at Penn State.

ITEM	VHF1, VHF2 and VHF3	UHF1
Type	Pulsed Doppler	Pulsed Doppler with RASS Option
Location	1: Near McAlveys Fort, PA 2: Near Crown, PA 3: Scheduled for ERICA Use	Currently at Penn State Circleville Farm
Frequency	1: 49.80 MHz 2: 49.92 MHz	404.37 MHz
Bandwidth	300 or 100 KHz	1 MHz, 330 KHz or 110 KHz
Peak Power	30 kW	9 kW
Pulsewidth	3.67 or 9.67 μsec	1, 3.67 or 9.67 μs
Antenna:		
Type	Phased Array Co-Co	Phased Array Co-Co
Dimensions	50 m x 50 m	8 m x 8 m
Angle(s)	75° and 90°	75° and 90°
On Site Computer	Data General Eclipse	Data General Eclipse
Time Domain Aver.	≃ 400 or ≃ 125	Selectable
Spectral Method	64 or 128 pt. FFT	64 or 128 pt. FFT
Spectral Aver.	8 or 16	Selectable
Minimum Detect. Range	≃ 1.0 km	≃ 370 m
Maximum Usable Range	≃ 18 km	≃ 12 km
Maximum Height Resolution	290 m	100 m

domain. Funds for its deployment and operation will be obtained from other sources.

In summary, we hope to have six profilers operating in the western Pacific during the field program. All the costs of deploying and operating these systems will essentially be provided by external sources, and the only obvious costs to this project will be to support data acquisition, transmission and processing.

d. Deployment strategy

In the field program data network (Fig. 1), proposed profiler locations are shown as arrows. The recommendation of the working group is that the Pennsylvania State University 50 MHz system be located on Iwo Jima. The rationale is that this system can observe the upper troposphere and is thus better able to observe outflow jets. This system is also a better substitute for a rawindsonde station than is a 405 MHz system. The U. S. Naval Postgraduate School 405 MHz system should then be located on Mimamidaitojima.

There was some discussion of possible sites for profilers if any additional systems become available for the field program. It was tentatively decided that the first choice for such a system would be at Clark AFB in the Philippines, where it would provide coverage to the left of the track (looking downstream) for non-recurving storms.

If possible, all of the profilers should operate throughout the duration of the field program. Given the expense of moving and installing the systems, there is little point in trying to save resources by reducing the time in the field. If the Japanese profiler can be relocated to Okinawa, it would be highly desirable that it remain on station throughout the observing period.

7. Satellite observations

a. Scientific justification

The routine observational system to support tropical cyclone motion research is sparse at best (Fig. 1). Consequently, remotely sensed data from satellites are essential for research studies and especially for forecasting support of the field experiment.

b. Technical aspects

The Japanese and USA satellites that are expected to be available for research and for forecasting support are listed in Table 3. The Geostationary Meteorological Satellite (GMS) imagery will be transmitted hourly rather than the present three hourly schedule. Operational cloud drift winds will be extracted and transmitted four times per day after 1 January 1989. A special extraction during typhoon situations based on 15 minute imagery also will be available once a day at about 04 UTC. A post-storm processing of the data to extract cloud drift winds with higher resolution four times a day is proposed by the University of Wisconsin.

Table 3 Japanese and USA satellite observing systems expected to be available during the summer 1990 field experiment.

Satellite	Data Type	Resolution	Frequency	Real Time	Archive	Comment
GMS (geost)	VIS	1 km	hourly	yes	McIDAS	dayligh
	IR	*4 km	hourly	yes	McIDAS	*4 times half-hou
	OP Winds	low	4 sets/day (max)	*yes	?	*unfrien format
	Wisc. Winds	high	4 sets/day	no	McIDAS	post processe
TIROS (polar orbit)	OP Soundings	250 km	100/overpass x4 over/day (max)	no	McIDAS	
	Wisc. Soundings	75 km	400/overx4/day (max)	no	Asheville/ McIDAS	post processe microwav option
	AVHRR VIS IMAGERY	1 km	4/day(max)	yes	Guam 2 weeks	
	IR IMAGERY	1 km	4/day(max)	yes	Guam 2 weeks	derived fields po
DMSP (polar orbit)	VIS	1 km	4/day(max)	yes	Guam 2 weeks	decoding necessar
	IR	1 km	4/day(max)	yes	Guam 2 weeks	
	SSM/I	15/50 km	4/day(max)	?	?	Experime Product
	SSM/T Soundings	250 km	?	no	?	GWC may process request

Operational processing of the TIROS soundings is expected to yield about 100 profiles per overpass. In a two-satellite scenario, this would result in a maximum of 400 profiles per day. Proposed post-processing (with the microwave option) at the University of Wisconsin is expected to increase the number of profiles by a factor of four and yield an average horizontal resolution of 75 km. AVHRR visible and infrared imagery with 1 km resolution should be available four times a day. The sea-surface temperatures can be estimated from the infrared imagery if required.

The polar-orbiting DMSP also will produce similar resolution visible and infrared imagery four times a day. One of the new instruments onboard the present DMSP is the SSM/I, which senses the rainfall rate and the sea surface wind field. Much research is in progress to extract the surface wind distribution in typhoons from the SSM/I observations. However, it is questionable whether another SSM/I will be in orbit during 1990, and if the algorithm development will be completed and validated by then. The DMSP also produces vertical temperature profiles with a horizontal resolution of about 250 km. This information may provide measurements between gaps in the TIROS data that are to be post-processed as indicated above.

It is proposed that an atlas and a videotape of the GMS imagery be produced for the period of the field experiment. It was generally agreed that this would serve as a convenient reference for researchers working with the field experiment data.

c. Archiving

Several nations in addition to Japan will receive the GMS data at one-hourly intervals. In addition, the sets of three half-hourly images for producing cloud-drift winds must be ingested and stored each 6 h. The primary archiving problem is to assure that these images always cover the area of interest for the field experiment.

High resolution TIROS and DMSP infrared imagery are received at the Joint Typhoon Warning Center (Guam) and are stored for approximately two weeks. As a backup, the Colorado Snow and Ice Center archives these data, but they may not be available until a year after the experiment. The DMSP SSM/I high resolution microwave imagery may or may not be available at Guam during the field experiment. A backup for these data is also uncertain.

d. Ranking

The ranking of the different satellite data types depends on the specific needs. If the primary purpose is for analyzing large/synoptic-scale features (subtropical ridge, midlatitude trough/cyclone interactions, etc.), the priorities are: 1) GMS imagery; 2) GMS cloud drift winds, especially the proposed post-processed data sets produced by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin; and 3) TIROS soundings, especially the enhanced sets produced by CIMSS;

and 4) SSM/I microwave imagery from DMSP. For mesoscale analysis (convective rings, inner core characteristics; and more accurate center locations, etc.), the priorities may be shifted to: 1) GMS imagery; 2) TIROS AVHRR high resolution imagery; 3) DMSP high resolution imagery; and 4) DMSP SSM/I microwave imagery.

Many studies of tropical cyclone motion require highly accurate storm center positions to derive relative wind fields. Without operational weather reconnaissance aircraft, this critical task must be based on satellite fixes. For a 1 m/s accuracy, the six hourly fixes must have an accuracy of 20 km. The fix accuracies must be even higher for shorter interval estimates of storm motion. Two options during the field experiment include using the JTWC (or other) best tracks or to generate a separate best track from the operational fixes. A third option is to generate a separate set of satellite fixes from post-analysis and then generate a final best track. This option either requires high quality hard copies with good grids or archiving of the digital data. The DMSP SSM/I could be especially useful for this task in weaker tropical cyclones. The detection of precipitation in the curving rainbands from this microwave imagery may be very useful in defining a center for these weaker tropical systems.

e. Cost estimate

Specific cost estimates are not available because of the uncertainties in field experiment requirements at this stage. CIMSS personnel will be preparing preliminary estimates in the coming months.

8. Surface Network Enhancement

a. Scientific justification

It is commonly thought that upper-air wind observations are the single most useful meteorological variable for tropical cyclone motion studies. Even with the rawinsonde ships in the network in Fig. 1, a large gap in upper-air coverage will exist over the southern Philippine Sea. Analysts must rely on aircraft reports and remotely-sensed observations to define the systems in these data-sparse areas. The surface ship reports over the sea and from small islands are essential in "tying-down" the low-level tropical analyses. Vertical soundings from satellites particularly need surface observations to increase accuracy.

b. Potential enhancements

(i) Drifting buoys. Two types of drifters are available: 1) Light-weight drifters are being developed that may be deployed through a sonobuoy chute. Present versions measure only surface pressure, air and sea-surface temperatures, and cost about $3,000. 2) Heavier buoys that might be deployed from ships, or from an aircraft that has a rear cargo ramp. These buoys measure surface winds as well as other variables listed above and cost about $9,000. The U. S. Navy has deployed several of the heavier buoys in support of the Joint Typhoon Warning Center (JTWC).

A major concern is the length of time that a drifting buoy will remain in the experimental area. Based on the records of Dr. Klaus Wyrtki (University of Hawaii), buoys deployed in the Philippine Sea between 15°N and 20°N and between 130°E and 140°E should remain within the experimental area for several months. Deployment south of 15°N will probably be carried by a strong westward current to the Philippine Islands. Buoys deployed west of 130°E may be swept northward by the Mindanao Current into the Kuroshio Current and be lost from the region.

(ii) Island station enhancement. The JTWC and the National Weather Service are cooperating in a program to install automatic surface observation systems (either the Remote Automated Meteorological Observing System - RAMOS, or the commercial HANDAR stations). As shown in Table 4, the proposed sites are in the Marshall Islands, the Northern Marianas and the federated states of Micronesia. Two of the proposed surface stations (Pagan and Farallon de Pajares) are at the same locations as the proposed additional rawinsonde sites in the plan in Fig. 1. According to the National Weather Service, the automated surface stations should be in place by 1990.

(iii) Ships of opportunity. The Comprehensive Ocean Atmosphere Data Set (COADS) file indicates that the average number of ship reports in the Philippine Sea per 6 h was

Table 4 List of proposed sites for installation of automated surface stations by JTWC and the National Weather Service.

USA PROPOSED HANDAR SITES

STN ID	PRIORITY	NAME	LAT(N)	LONG(E)	EL(M)
	1	Gaferut Island	09 14	144 23	2
91343	2	Ujelang Atoll	09 46	160 58	3
	3	Farallon de Pajaros	20 32	144 55	
	4	Oroluk Atoll	07 38	155 09	
91222	5	Pagan Island	18 06	145 46	6
91322	6	Ulul Island	08 35	149 40	3
91254	7	Bikini Atoll	11 31	165 33	3
91323	8	Satawal Atoll	07 21	147 02	3
91442	9	Ebon Atoll	04 35	168 43	3
91314	10	Sonsorol Atoll	05 19	132 13	3
	11	Sorol Atoll	08 08	140 24	
91250	12	Enewetak Atoll	11 21	162 20	5
	13	Eauripik Atoll	06 42	143 03	
	14	Ngulu Atoll	08 18	137 29	
	15	Ngatik Atoll	05 50	157 10	
	16	Ujae Atoll	08 56	165 45	
91601	17	Butaritari Atoll	03 05	172 48	
	18	Taongi Atoll	14 38	169 00	
	19	Wotho Atoll	10 11	166 01	
	20	Maloelap Atoll	08 42	171 14	

about 20 during 1970-79. The number of daytime observations is slightly larger (60% to 40%) than during the night. Ship reports received at Fleet Numerical Oceanography Center (Monterey) in selected years during the 1980's are generally consistent with the COADS average.

Although a Japanese fishing fleet operates in Marianas waters, JTWC has had no success in obtaining meteorological observations from them. Efforts to obtain data from other fishing vessels also have failed.

Some increase in transmitting ship reports may result from special requests by the forecast offices when storms are present. However, better warnings tend to reduce the number of ships that are caught in storms and thus reduce observations near the center.

c. Deployment costs

The larger drifting buoys have been deployed with C-130 or C-141 aircraft tasked under a Special Assigned Airlift Mission (SAAM). The average cost for a SAAM mission to deploy nine drifting buoys in the Philippines Sea is approximately $39,000. The alternative of a ship deployment is extremely costly, with ship costs that range from $8,000 per day to $15,000 per day. For example, assume a university research vessel at $8K/day requires 11 days to deploy six buoys at a 5° lat./long. spacing between 15° and 20°N and 130° and 140°E. Thus, the deployment of only six buoys would cost $54K for hardware and $88K for ship time for a total of $142K.

Consider the deployment of the smaller buoys from Navy aircraft (no direct cost, but also little or no control on the timing of the deployment pending other requirements). A 2.5° by 2.5° lattice would require 15 buoys at \$3K for a total cost of \$45K. A 5° lattice would require only 6 buoys at \$3K, or \$18K.

Deployment of the automated surface stations will not be funded from project funds. Since a ship must be contracted to deploy the stations on these remote islands, the initial cost per station is so high that it is unrealistic to consider funding additional stations from the very limited project funds.

d. Operating costs

Communications with the drifting buoys (and automated surface stations) will be via the ARGOS tracking and relay system. Transmissions via polar orbiting satellites would yield 8 observations per day per buoy. This expense is relatively minor in relation to capital and deployment costs. Perhaps as in the case of the automated surface stations, operating costs might be funded from another source.

e. Summary

Only 20 ship reports per 6 h are expected in the Philippine Sea. Installation of two automated surface stations in the Northern Marianas will increase the coverage on the eastern boundary of the experimental domain.

Additional rawinsondes are also planned at these two stations for the field experiment (Fig. 1).

Only the lightweight drifting buoys deployed from Navy P-3's appear to be a viable option to consider in enhancing the surface network during the field experiments. If the RAOB ship network in Fig. 1 is indeed available, the proposed array of drifting buoys would be somewhat redundant. Consequently, this proposal would have a lower priority relative to other proposal upper-air network enhancements.

9. Aircraft

a. Scientific justification

Research aircraft provide a mobile platform that can be tasked to investigate specific areas of interest. For example, only aircraft can measure radial profiles of wind or obtain detailed observations of the structure of an outflow jet. Research aircraft dispensing dropwindsondes can contribute to the field experiment in two ways: by supplementing the planned rawinsonde network in the Philippine Sea where no islands exist or by providing an increased density of observations near the typhoon. In either case, aircraft data would be available only during enhanced observing periods because crew rest and maintenance requirements would prevent flying every day. To be useful, the aircraft must have a ceiling in the midtroposphere or above and should have a range of > 2500 n mi. Four-engine turboprop aircraft meet this requirement and are traditional for this application. Jet aircraft offer substantial advantages since their ceiling approaches the tropopause and their higher ground speed makes their observations more nearly synoptic. In summary, even a single properly configured aircraft could provide valuable augmentation of the network at one synoptic time per day during intervals of intensive observations.

b. Possible aircraft

(i) Air Force C-130. A request has been initiated for three Air Force C-130's for one month or for two planes for 45 days. This request is on hold until the future of air reconnaissance in general is addressed by the U.S. Congress. If the Air Force continues to operate the existing aircraft, the first priority is for reconnaissance of Atlantic hurricanes and tropical cyclones threatening Hawaii or the west coast of the USA. The Air Force has committed up to 500 Omega-based dropwindsondes to the experiment regardless of the availability of the Air Force planes.

(ii) NASA DC-8. The DC-8 would be ideal for this experiment because the range exceeds 4000 n mi and it has a ceiling above 200 mb. This aircraft does not have a dropchute, although it is in the future instrumentation plans. Commitment of this plane to the western North Pacific for an extended period would require other cooperative experiments such as the testing of future satellite microwave instruments or the Laser Atmospheric Wind Sounder.

(iii) NCAR Sabreliner. Although this aircraft has a 200 mb ceiling, it only has a 1300 n mi range. It could dispense the fast-falling LORAN-based dropwindsondes developed at NCAR for an extratropical cyclogenesis experiment in the western North Atlantic during December 1988-February 1989. Long, overwater flights in the tropical cyclone environment would be possible only if landing privileges at Iwo Jima are granted. Then flights between Guam and Iwo Jima and between Okinawa and Iwo Jima could provide some excellent scientific data in the upper levels of tropical cyclones. Participation of this aircraft would be dependent on the success of a University of Wisconsin proposal to the National Science Foundation to study tropical cyclone intensification.

(iv) NCAR Electra. This four-engine aircraft is not suitable for penetrations into the inner core of a tropical cyclone. However, it would be very useful to study the structural changes accompanying tropical cyclone intensification, especially in relation to the structure below an outflow jet during interaction with a midlatitude trough. Although the NSF proposal by Colorado State University will be to study tropical cyclone intensification, the data obtained by the Electra would be very useful for tropical cyclone motion studies as well.

(v) NOAA WP-3. These aircraft have exceptional capabilities for tropical cyclone research. For example, the P-3's have Doppler radar and a three-channel omega dropwindsonde equipment that would provide the vertical profiles of horizontal wind from 400 mb to the surface. Such profiles would be useful to test the hypotheses in the field experiment. However, it presently appears that the P-3's can not be more than a 24-h flight from Miami during the Atlantic hurricane season. Deployment to the western North Pacific during August and September 1990 would set a precedent that could endanger hurricane research by HRD with the P-3's in future years.

c. Costs

In addition to the flight hours in support of the field experiment, a significant cost is involved in simply ferrying the aircraft to and from the USA. With say 10-11 experimental missions of 10 h duration, a total of 150 flight hours might be required for a four-engine turboprop aircraft. An order of magnitude cost would be perhaps $400K.

The present cost of the NASA DC-8 is about $5.6K per hour. For eight experimental missions of say 8 h, the cost again exceeds $400K. As indicated above, cost-sharing would be necessary for the DC-8 to participate.

As the participation of either the NCAR Sabreliner or the Electra would be funded separately, no estimates have been made of these costs.

10. Experimental Forecast Support

a. Scientific justification

A forecast support group is absolutely essential for the success of the field experiment. The tasks of this group would include preparing forecasts necessary for planning experimental phases, all aircraft operations, initiating and terminating special observations, and to ensure the safety of personnel manning the ships and remote stations. The forecast group would coordinate with the Asian national meteorological centers, especially if a second Typhoon Operational Experiment (TOPEX-II) is in progress at the same time as this field experiment.

b. Possible locations

JTWC provides the logical forecasting site because of the extensive forecasting and communications support facilities existing there. The overall experiment control/coordination office also should be established in Guam.

A second potential choice is the TOPEX-II office, but this has political ramifications. It would be preferable to operate out of Guam, but maintain close liaison with TOPEX-II. One member of the team could visit TOPEX for a short period.

The plan is to supplement and work with the current JTWC operations rather than establish a separate forecast office. We estimate that this will require 2-3 people providing forecast support and contributing to the experiment coordination effort during the intensive experimental phases. The minimum requirements are for G. Holland plus one other forecaster. A student also may be needed to provide help with special techniques, data encoding, etc. The forecasters would interact with JTWC throughout the forecast process, but would then provide special forecast consultative advice to the experiment. For safety reasons, one person must be on duty the entire period to monitor any dangerous situations. This person could be a JTWC forecaster for intervals between the intense observational periods.

c. Requirements

Travel costs for 2-3 people for 1-2 months. Assuming that they can be accommodated in the BOQ, approximately $10-15K would be required.

(i) <u>Communications</u>. We will need to have maximum inward communication of field data to JTWC. We also will need to be able to directly contact outlying stations, ships, etc., and to be able to communicate with the TOPEX II office. Costs and methods for establishing these communications are unknown as this stage.

(ii) <u>Microcomputers</u>. We will need at least one and preferably two dedicated microcomputers. These could be shared with the experiment coordination team. We suggest that these can be borrowed and the costs only will be for transportation.

(iii) Archival. Onsite, real-time archival of the experimental data should be attempted. This would include cyclone tracks, together with incoming sounding, buoy, satellite data. Costs would be for rapid-write tapes connected to a communication computer and to one of the experiment microcomputers. Further investigations are needed on the method, the costs and the volume of data.

d. JTWC Support

G. Holland visited JTWC in August and discussed preliminary plans and logistics requirements. There is strong support for the experiment and the whole ONR initiative, and indications are that JTWC/NOCC Marianas will be very helpful. The space and support for the forecasting/command offices should be made available. Communications in and out of Guam are already excellent. However, significant additional communications will be required, especially to get outlying station reports and comprehensive GTS data directly into the forecast center.

e. Future plans

A more detailed forecast schedule will be prepared for discussion at the next workshop. This will include all types of forecasts that will be required and the methods to be used. Some limited research may be required to support the forecast group. Further coordination with JTWC will be required prior to the experiment. For example, testing of the communications systems should be undertaken during 1989.

11. Future research thrusts

a. Theoretical studies

A topical listing of the future theoretical studies by attendees of the workshop is included in Table 5. This overview indicates a wide range of approaches by project personnel and by other contributing agencies (affiliations given in Appendix A). The general feeling is that additional nondivergent barotropic and shallow-water models are not required, although some new topics may profitably be addressed with the existing models. Thus, it is encouraging to note that most of the future studies involve baroclinic model approaches.

b. Observational studies

Some data sets that are suitable for various aspects of tropical cyclone motion research are listed in Table 6. In addition to climatological studies, two other approaches commonly used are the composite studies and case studies. Some of the new approaches also incorporate a numerical model. For example, the model initialized fields may be used to "fill in" spatial details between observation sites and in time, especially for diagnostic studies. A second example is to integrate the model with only the symmetrical component of the cyclone to compare the asymmetries from the model with those in the analyses. Other permutations of the combined numerical-observational technique are possible.

The major aim of the observational research should be to investigate the mechanisms and effects of tropical

Table 5 Summary of theoretical, numerical and laboratory research studies of tropical cyclone (TC) motion by attendees at workshop (Note: Some of these studies are not funded by the project, but contribute to understanding of TC motion).

	Approach	Model	Topic
Carr	Analytical	Nondivergent barotropic	Vortex adjustment to asymmetric forcing
Evans & Holland	Numerical	Shallow water	TC-subtropical ridge interaction
Krishnamurti	Numerical	Nondivergent barotropic	Real data sensitivity studies
Morton	Laboratory	Rotating table	Effects of bottom friction on shallow vortex
Schubert	Numerical	Nondivergent barotropic	Initialization & data assimilation processes
Shapiro	Numerical	Baroclinic	Vortex structure effects on initialization Vortex adjustments by eddy fluxes
Smith	Numerical	Barotropic Baroclinic	TC-Rossby wave interaction
Stevens	Numerical	Baroclinic	TC-environmental flow
Wang	Numerical	Baroclinic	Physical effects in TC motion
Willoughby	Numerical	Baroclinic	Physical & environmental flow effects
Yamasaki	Numerical	Baroclinic	Convective effects on TC motion

cyclone interaction with the environment. Particular emphasis should be given to research that can help with planning the field experiment and that provides refinement or extension of the working hypotheses. Some specific research recommendations related to the issues in Section 2 follow.

Cyclone-environment interactions. Environmental interactions occurring during recurvature should be given the highest priority in the observational studies. As indicated in Hypothesis A and B, interactions with the subtropical ridge, midlatitude troughs and TUTT cells should be documented to the extent possible with the data sets in Table 6.

Relatively little is known about the basic processes associated with tropical cyclone interactions with the subtropical ridge. More information is required on the structure of the ridge and its time variability. Barotropic interactions might be explored first by documenting the ridge structure and the motion of different size cyclones relative to the ridge. Baroclinic effects might then be included.

A more detailed understanding of tropical cyclone interaction with midlatitude troughs is needed. Better documentation of the conditions for which tropical cyclones recurve or do not recurve are required. A special focus should be given to the mechanisms through which a cyclone can connect with and amplify the trough.

Table 6 Observational data sets for tropical cyclone studies

Title	Responsible agency	Comments
AMEX	Bureau of Meteorology	Australian Mesoscale Experiment in 1987 included two TC
CSU	Colorado State University	20-30 y rawinsonde data for various ocean basins plus recon data in western North Pacific
TOPEX	WMO/ESCAP Typhoon Committee	Typhoon Operational Experiment in western North Pacific
HRD	Hurricane Research Division (NOAA)	Especially synoptic flow experiment data sets
Sadler	University of Hawaii	Wind analyses at 250 mb, especially for TUTT studies
CIMSS	University of Wisconsin	Data for eight TC in North Atlantic, including water vapor channel satellite observations
OPER	ECMWF, NMC, FNOC, Bureau of Meteorology	FGGE data sets of ECMWF widely distributed
MISC	Various individuals and agencies	Special analysis for case studies, such as hurricane Frederic in Gulf of Mexico

Similarly, tropical cyclone motion relative to TUTT cells needs further documentation. These studies may also have to include vertical interactions with the subtropical ridge. If it is found that the data sets in Table 6 are inadequate for these studies, a statement of requirements for the field experiment should be generated.

Beta-gyres. Important observational questions include the vertical structure, the orientation relative to the moving cyclone, and the effects that different environmental flows have on these gyres. An immediate goal should be to demonstrate the effects of gradients in relative vorticity on gyre generation and cyclone motion.

Propagation versus advection. Observational studies should now examine the effects of different storm sizes on the working definition of the advection (the mean wind in the 5^{o}-7^{o} latitude radial band). A second goal should be to determine if the vortex does move almost exactly with the speed of the mean flow in the inner core as the isolated vortex model studies suggest.

Vortex profiles. A particularly important question is whether tropical cyclones are isolated in the sense that the integrated relative angular momentum tends to zero within one Rossby radius of deformation. Explanations are required for why vortices in barotropic models tend toward zero angular momentum profiles, whereas this tendency is not observed in baroclinic models or in the observations.

12. Conclusions

The objective of this report has been to report the progress on the ONR Tropical Cyclone Motion initiative. Five issues that are the focus of the initiative are described in Section 2. Four of the five tentative hypotheses from the January 1988 workshop have been combined into two hypotheses and a new hypothesis has been added (Section 3). A major goal of this workship was to begin discussing the field experiment in the western North Pacific during August and September 1990. A "strawman" network of ship-based rawinsondes, additional land rawinsondes and radar wind profilers was presented (Fig. 1) to promote discussion of the hypotheses (Section 4). Provisional working groups were formed to begin specific plans for observational systems and an experimental forecast support team. The preliminary working group reports are included in Sections 5-10. Finally, some plans for future theoretical and observational research studies are summarized in Section 11.

The next workshop is planned for the week following the 18th Hurricane and Tropical Meteorology Conference in San Diego, California during May 1989. The location is uncertain, but it will probably be in Southern California. This workshop will be the last meeting prior to drafting the field operations plan, which will be published later in 1989.

ACKNOWLEDGEMENTS

Arrangements for the workshop in Rainbow Beach were made by Roger Smith. The exceptional setting and the congeniality of the participants contributed to a productive workshop. Discussions were led by G. J. Holland, H. Willoughby and W. Schubert. Summaries of these discussions by rapporteurs J. C.-L. Chan, D. Stevens and R. Smith contributed much to the preparation of this report. Similarly, the working group reports by W. Frank, C. Velden and R. Merrill, T. Schroeder, H. Willoughby and G. Holland are important contributions. Finally, W. Schubert and G. Holland summarized the theoretical and observational research plans.

Preparation of the workshop report has been supported by the Naval Postgraduate School direct research funding. G. Holland reviewed the manuscript, which was skillfully prepared by Mrs. P. Jones.

REFERENCES

Chan, J. C.-L., 1986: Supertyphoon Abby--An example of present track forecasting inadequacies. Weather and Forecasting, **1**, 113-126.

Chan, J. C.-L., and W. M. Gray, 1982: Tropical cyclone movement and surrounding flow relationships. Mon. Wea. Rev., **110**, 1354-1374.

DeMaria, M., 1985: Tropical cyclone motion in a nondivergent barotropic model. Mon. Wea. Rev., **113**, 1999-2110.

Elsberry, R. L., 1986: Some issues related to the theory of tropical cyclone motion. Technical Report NPS 63-86-005, Naval Postgraduate School, Monterey, CA 93943, 23 pp.

Elsberry, R. L., 1987a: Potential observing systems for tropical cyclone motion studies. Technical Report NPS 63-87-003, Naval Postgraduate School, Monterey, CA 93943, 47 pp.

Elsberry, R. L., 1987b: Interim review of the possibilities and opportunities for the Office of Naval Research Tropical Cyclone Motion Research Initiative. Technical Report NPS 63-87-007, Naval Postgraduate School, Monterey, CA 93943, 31 pp.

Elsberry, R. L., 1988: ONR Tropical Cyclone Motion Research Initiative: First-year review, discussion and tentative hypotheses. Technical Report NPS 63-88-003, Naval Postgraduate School, Monterey, CA 93943, 86 pp.

Fiorino, M., 1987: The role of vortex structure in tropical cyclone motion. Ph.D. dissertation, Naval Postgraduate School, Monterey, CA 93943, 370 pp.

Fiorino, M., and R. L. Elsberry, 1988: Some aspects of vortex structure related to tropical cyclone motion. Accepted, J. Atmos. Sci.

Frank, W. M., 1977: The structure and energetics of the tropical cyclone, I. Storm structure. Mon. Wea. Rev., **105**, 1119-1135.

George, J. E., and W. M. Gray, 1976: Tropical cyclone motion and surrounding parameter relationships. J. Appl. Meteor., **15**, 1252-1264.

Holland, G. J., 1984: Tropical cyclone motion: A comparison of theory and observation. J. Atmos. Sci., **41**, 68-75.

Kasahara, A., and G. W. Platzman, 1963: Interaction of a hurricane with a steering field and its effect upon the hurricane trajectory. Tellus, **15**, 321-335.

Peterson, V., 1987: Wind profiling: The history, principles, and applications of clear-air Doppler radar. Informal report available from Tycho Technology, Inc., P. O. Box 1716, Boulder, CO 80306.

APPENDIX A

LIST OF ATTENDEES

Name	Affiliation
R. Abbey	Office of Naval Research
T. Arafiles	PAGASA, Philippines
L. Carr	Naval Postgraduate School (NPS)
J. Chan	Royal Observatory, Hong Kong
R. Elsberry	NPS
J. Evans	Monash University, Australia
W. Frank	Penn State University
W. Gray	Colorado State University
G. Holland	Bureau of Meteorology, Australia
T. Krishnamurti	Florida State University
C.-S. Lee	National Taiwan University
R. Merrill	University of Wisconsin
B. Morton	Monash University
M. Peng	NPS
M. Reeder	Monash University
T. Schroeder	University of Hawaii
W. Schubert	CSU
L. Shapiro	Hurricane Research Division (HRD)
R. Smith	Monash University
D. Stevens	CSU
C. Velden	University of Wisconsin
B. Wang	University of Hawaii
F. Wells	Joint Typhoon Warning Center
H. Willoughby	HRD
M. Yamasaki	Meteorological Research Institute, Japan

APPENDIX B

ONR TROPICAL CYCLONE MOTION ACCELERATED RESEARCH INITIATIVE

MID-YEAR REVIEW

29 June - 1 July 1988
Rainbow Beach, Queensland

AGENDA

Wednesday 29 July 1988

0830	Registration/Introductions
0835	Workshop Objectives - Russ Elsberry
0850	ONR Status Report - Bob Abbey
0905	Bill Gray - Surrounding Flow Influences on Tropical Cyclone Motion
0945	Morning Tea
1000	Hugh Willoughby - More About Linear Vortex Motion Melinda Peng - The Beta Effect and Tropical Cyclone Motion Les Carr - Barotropic Stability of an Axisymmetric Vortex Roger Smith - Some Numerical Experiments on Barotropic Vortex Motion
1215	Lunch
1330	Johnny Chan - Numerical Model Investigation of Mean Flow Influences on Tropical Meteorology Greg Holland - Model and Observational Diagnostics of Tropical Cyclone Motion Lloyd Shapiro - Vortex Motion on a Beta Plane
1515	Afternoon Tea
1530	Krishnamurti - Hurricane Track Forcing with a High Resolution Global Model Tom Schroeder - Planned Tropical Cyclone Motion Research at the University of Hawaii
1630	Close

Thursday 30 July 1988

0830	Wayne Schubert - The Use of the Adjoint Method in Tropical Cyclone Motion Forecasting

	Greg Holland - The NEPRF Tropical Cyclone Motion Project
0945	Morning Tea
1000	Discussion Session #1 - Status of Observational Studies Discussion Leader - Greg Holland Rapporteur - Johnny Chan
1145	Lunch
1300	Discussion Session #2 - Status of Theoretical Studies (Including Laboratory Modeling) Discussion Leader - Hugh Willoughby Rapporteur - Duane Stevens
1445	Afternoon Tea
1500	Discussion Session #3 - Status of Numerical Modeling Studies Discussion Leader - Wayne Schubert Rapporteur - Roger Smith
1645	Close

Friday 1 July 1988

0830	Discussion Session #4 - Field Experiment Status and Planning Discussion Leader - Russ Elsberry Rapporteur - Bill Frank
1000	Morning Tea
	Working Group Discussions
1200	Lunch
1330	Discussion Section #4 continued/ Working Group Reports
1500	Afternoon Tea
1515	Summary of Discussion Session #4 Concluding Discussion
1630	Close

APPENDIX C

SUMMARIES OF RESEARCH

Summaries or short abstracts of recent progress have been submitted by ONR contractors and other participants (see affiliations in Appendix A):

Progress Report on Tropical Cyclone Motion Research

July 1988

LCDR L. E. CARR III
Naval Postgraduate School
Monterey, California

This progress report consists of two parts: i) a theoretical model that explains vortex stability to horizontal asymmetric forcing; and ii) an analysis of composite observational data that provides evidence of the β-induced motion of a tropical cyclone (TC) relative to environmental steering.

1. Vortex Stability: Using a nondivergent barotropic numerical model on a β-plane, Chan and Williams (1987) showed that a linear vortex disperses rapidly due to Rossby wave radiation, although the motion of the vortex center is negligible. However, a nonlinear vortex resists dispersion and exhibits a significant center motion of about 2 m/s to the northwest (Northern Hemisphere). This result suggests that vortex motion and vortex stability due to nonlinear processes are closely related.

To identify the stabilizing mechanism, I have developed a nondivergent barotropic analytical model on an f-plane that predicts the time evolution of linear asymmetric initial perturbations in response to advection by a sheared, time-invariant and axisymmetric vortical flow. The vortical flow is chosen to be pure Rankine within an annular domain in order to isolate the process of advection of perturbation vorticity by the sheared symmetric flow. Because the perturbations become tilted in the direction of the shear, they are barotropically damped in a manner analogous to that in the plane Couette flow problem (Case, 1960). The rate of damping is proportional to the magnitude of the radial shear of the tangential winds, which may explain in part why the winds in the TC become increasingly axisymmetric as the center is approached. The rate of damping is proportional to the square of perturbation azimuthal wavenumber, which is consistent with observational evidence that TC asymmetries are predominantly azimuthal wavenumber one.

Several extensions of this research are being pursued. As suggested by Hugh Willoughby at the Rainbow Beach workshop, I am making an approximate calculation of the radial convergence of momentum flux from the perturbation to the symmetric vortex due to the damping process. This calculation should provide some insight into how asymmetric environmental forcing may result in intensity or outer wind strength changes in the TC. I am also extending the model to include non-Rankine symmetric vortical flows to determine how advection of symmetric vorticity by initial perturbations will modify vortex stability. Ultimately, this model will include the β-effect and non-zero environmental winds with the goal of explaining vortex motion deviations from steering in terms of a balance between asymmetry-inducing external forcing and asymmetry-damping vortex stability.

2. Observational evidence for the β-effect: A number of compositing studies (George and Gray, 1976; Chan and Gray, 1982; Holland, 1984) have identified significant differences between TC motion and variously defined "environmental steering" flows. Fiorino's results (1987) suggest that this deviation is due to an additional steering component induced by nonlinear interaction of the TC with environmental potential vorticity gradients. However, Holland (1983,1984) has suggested that this difference is due to a Rossby wave-like propagation of the TC relative to environmental steering, based on the assumption that the steering flows computed from real data already include the TC-induced steering component. At the Rainbow Beach workshop, Bill Gray suggested that the deviation from steering is primarily a baroclinic phenomenon.

To address this issue, I have reexamined the data from the composite studies cited above by expressing the deviation of TC motion from steering as a geographically-oriented vector difference for each composite stratification. The direction of this difference vector is always between SW and NW and the magnitude is typically 1.0-2.5 m/s. Although the vector magnitude is suggestive of the β-effect, it is difficult to attribute the significant southwest components of the some of these difference vectors to a TC-induced contribution to environmental steering, even if allowance is made for the presence of large-scale vorticity gradients. A complicating factor is that each study used a different domain over which to compute the steering flow.

A problem with computing the difference between TC motion and steering is that the result contains unknown contributions from the three mechanisms identified above. The effect of a TC-induced contribution to barotropic steering may be isolated by subtracting an appropriately defined TC-independent "outer steering flow" from a TC-modified "inner steering flow". Although the "outer steering" is clearly an idealization, a reasonable approximation would be a pressure-weighted average wind over an annulus of 5°-7° latitude radius. An "inner steering" should be accurately represented by a pressure-weighted average wind over an annulus of 1°-3° latitude radius. I have made a rough calculation of such a steering flow difference by subtracting a 5°-9° annulus steering "level" from a 1°-7° annulus steering "level" using data from George and Gray (1976). The resulting difference vectors are consistently in the NW quadrant with magnitudes ranging from 0.5 to 3.5 m/s, which is strongly suggestive of a TC-induced contribution to barotropic environmental steering. I have requested from Bill Gray the necessary composite data to more precisely compute the "TC-induced steering" using the inner and outer steering flow definitions stated above. The value of this approach is that an accurate identification of TC-induced contributions to a barotropic "outer steering" would then permit deviations of TC motion relative to an "inner steering" to be associated and analyzed with respect to the remaining propagation and baroclinic mechanisms suggested by Holland and Gray respectively.

3. References

Case, K. M., 1960: Stability of plane Couette flow. *Phys. Fluids, 8,* 143-148.

Chan, J. C.-L., and W. M. Gray, 1982: Tropical cyclone movement and surrounding flow relationship. *Mon. Wea. Rev., 110,* 1354-1374.

-----, and R. T. Williams, 1987: Analytical and numerical studies of the beta-effect in tropical cyclone motion. Part I: Zero mean flow. *J. Atmos. Sci., 44,* 1257-1265.

Fiorino, M., 1987: The role of vortex structure on tropical cyclone motion. Ph. D. Dissertation, Naval Postgraduate School, 369pp.

George, J.E., and W. M. Gray, 1976: Tropical cyclone motion and surrounding parameter relationships. *J. Appl. Meteor., 15,* 1252-1264.

Holland, G. J., 1983: Tropical cyclone motion: Environmental interaction plus a beta effect. *J. Atmos. Sci., 40,* 328-342.

-----, 1984: Tropical cyclone motion: A comparison of theory and observation. *J. Atmos. Sci., 41,* 68-75.

Barotropic Vortex Motion in a Uniform Shear Environment
by
Johnny C.-L. Chan and R. T. Williams

As discussed in the last Workshop report, a vortex under the influence of a uniform zonal shear ($U = \alpha y$, U = zonal wind, y = meridional distance and α = constant) will experience both wavenumber-one and wavenumber-two asymmetries. The wavenumber-one gyres (the beta gyres as termed by the current workshop) are affected not only by the symmetric part of the vortex circulation, but also by the environmental flow. The shear in the environment tends to rotate the β-gyres and change the vortex direction of movement. As a result, the northward displacement of a vortex for $\alpha < 0$ (cyclonic shear) is less than that for $\alpha > 0$ (anticyclonic shear).

To study these asymmetries in more detail, the model is first integrated with $\beta = 0$ with no nonlinear effects. The results clearly show a wavenumber-two asymmetry. If β is included in the linear model, the wavenumber-one gyres develop and are distorted by the environmental shear as well as the symmetric vortex circulation. Rotation of the β-gyres occurs when nonlinear effects are introduced. As in the case of Fiorino (1987), the axis of the gyres is perpendicular to the direction of movement of the vortex. For $\alpha > 0$, the rotation caused by the environmental flow is opposite to that by the symmetric vortex circulation. Thus, the vortex moves almost due north. On the other hand, for $\alpha < 0$, these two components "cooperate" and cause a large cyclonic rotation of the β-gyres. The vortex thus has a smaller northward displacement.

At the time of this writing, the effect of the wavenumber-two asymmetry has yet to be investigated. The case of parabolic jet will also be studied as this profile introduces a constant vorticity gradient.

AN INVESTIGATION OF TROPICAL CYCLONE MOTION DURING INTERACTIONS WITH THE MONSOON TROUGH AND THE SUBTROPICAL RIDGE

Jenni L. Evans[1] and Greg J. Holland[2]
Naval Postgraduate School, Monterey

The aim of this study is to examine the barotropic interactions occurring between a tropical cyclone and both the monsoon trough and subtropical ridge. The method is to utilise both numerical modelling and case studies to investigate the types of barotropic interactions that can occur between a cyclone-like vortex and a subtropical ridge/monsoon trough environment. Particular emphasis is being given to potential recurvature situations. We expect that the results of this work will be a useful guide for the planning of the 1990 Tropical Cyclone Motion Field Experiment in the Northwest Pacific ocean basin.

1. The Model

The model is an inviscid, divergent, shallow water equations model on a southern hemispheric beta-plane, where beta is evaluated at $10^{o}S$ and the equivalent depth is 5.2km. The domain is $40x40^{o}$ latitude with 0.2^{o} resolution in each direction. The variables are located on an Arakawa C-grid and the spatial differencing follows that of Arakawa and Lamb (1981). A channel domain was used with walls at the northern and southern boundaries and east)west cyclic boundary conditions. Time differencing is that of Miller and Pearce (1974).

2. Initialization

The model is initialized with the climatologically derived vortex of Holland (1980), which is in gradient wind balance and is given by

$$h = h_o(1-e^{[-a/rb]}) + H \tag{1}$$

and

$$V_{TANG} = \{grdh/dr + r^2f^2/4\} - rf/2 \tag{2}$$

---

[1]Permanent affiliation, Centre for Dynamic Meteorology, Monash University, Melbourne, Australia

[2]Permanent affiliation, Bureau of Meteorology, Melbourne, Australia

where $b=1.5$, $a=r_m^b$, $f=f_o+y\beta$, $H=5.2$km and $h_o=500$m is equivalent to a 50hPa pressure drop between the cyclone centre and the surrounding environment.

3. Results Thus Far

Thus far, we have investigated the motion of an isolated vortex and the same vortex located between an idealised monsoon trough and subtropical ridge. The isolated vortex provides a control case for comparison with our trough/ridge interaction investigations and with other modelling studies.

As the divergent vortex evolves it develops wavenumber 1 asymmetries in the height and wind fields, and a divergence quadrapole. The wavenumber 1 asymmetry consists of the familiar 'beta-gyre' pattern. Video animation techniques are being used to examine the evolution of these gyres with time. Preliminary results indicate that the gyres vary significantly with time. Such variations could be an important component of interactions between a cyclone and its environment.

The asymmetric fields observed here agree well both with the AMEX datasets and with the deep layer mean asymmetric fields from three-dimensional ATCM spin-up vortex. This indicates that the barotropic component alone can provide some useful insights into the physics of the cyclone system.

Both the vortex symmetric height field and the divergence quadrapole pulse with time. The details of this pulsing are being examined.

The idealised trough/ridge system is initialized as a sine function in height varying in latitude only and with maximum amplitude of 50m. A balanced, cosine wind field also is specified. The model then is initialised by a linear addition of this trough/ridge and the vortex described above. As a result of this superposition the net system must adjust to a balanced state in the first hour or two of integration.

The basic beta-gyre pattern that is oriented east-west for the isolated vortex is rotated to a southeast-northwest orientation in this experiment. As a result, the beta-gyres strengthen the monsoon trough ahead of the cyclone and strengthen the subtropical ridge behind the cyclone. This causes an apparent break in the ridge to the southwest. The combined effect is for the cyclone to move towards the southwest, into the ridge and gradually recurve. However, the poleward movement is 30% slower than that for the isolated vortex. This smaller propagation speed could have resulted from the gradient of relative vorticity between the ridge and trough opposing the earth gradient. The observed rotation of the gyres also could have had an effect. We are investigating these processes further.

Additional studies will examine the motion of a vortex located on the ridge, on the trough, and poleward of the subtropical ridge. The modelling results will be tested on case studies of similar situations in the Northwest Pacific Ocean.

THE POCKET TROPICAL CYCLONE MODEL: PTCM87

Jenni L. Evans[1] and Greg J. Holland[2]
Naval Postgraduate School, Monterey

and

Ted Tsui
Naval Environmental Prediction Research Facility
Monterey

1. Research Objective

The research objective for the PTCM87 is to develop an effective forecasting scheme containing the major components of tropical cyclone motion while being simple enough for use on any microcomputer. The system described in this report has been developed for use in the Australian Tropical Cyclone Warning Centres (TCWCs) and the Joint Typhoon Warning Center (JTWC) in Guam.

PTCM87 runs on a remote microcomputer by first accessing analysis and prognosis fields from a central meteorological centre, removing the cyclone perturbation, then utilizing the basic motion equations of Holland (1983) to produce a cyclone forecast.

The forecasts are produced automatically by using past cyclone motion and analyses to set the required parameters. However, the scheme is designed for maximum 'hands on' accessibility, allowing forecasters to modify a range of parameters and to test the forecast sensitivity in real time.

A brief description of the model, of the forecast process and some preliminary forecast statistics are given in the following sections.

2. Basis of PTCM87

PTCM87 parameterizes the physical processes of advection by the large scale flow and Rossby mode propagation arising from the cyclone rotation across a gradient in Earth vorticity to predict tropical cyclone motion. The equations for the direction

---

[1]Permanent affiliation, Centre for Dynamic Meteorology, Department of Mathematics, Monash University, Melbourne, Australia.

[2]Permanent affiliation, Bureau of Meteorology Research Center, Melbourne, Australia

and speed of the cyclone motion are derived from the barotropic, nondivergent vorticity equation with a closure dependent on the size, r_E, of the cyclone (Holland, 1983)

$$theta_m = atan\{[[(1-x^2)/r_E^2]V_B sin(alpha)+beta]/[[(1-x^2)/r_E^2]V_B cos(alpha)+gamma(2-x) beta]\} \quad (1)$$

and

$$V_C = V_B cos(theta_m - alpha) + [beta\ r_E^2/(1-x^2)][sin(theta_m) + gamma(2-x) cos(theta_m)] \quad (2)$$

where V_C,$theta_m$ are the predicted cyclone motion, V_B,alpha are the large scale flow velocity, beta is the gradient of Earth vorticity, x defines the shape of the symmetric wind profile and gamma is the degree of convergence into the cyclone. Further assumptions incorporated into equations (1) and (2) are that the environmental advection is uniform across the cyclone and hence that large scale vorticity gradients and divergence do not affect the motion.

3. The PTCM87 Forecast Cycle

The microcomputer based forecast cycle proceeds as follows

(1) The current analysis and 12 hourly prognosis fields are downloaded to the microcomputer.

(2) r_E is evaluated by hindcasting the past 12 hours motion using equations (1) and (2) to determine the value that minimizes the error between the current and hindcast positions. This value of rE is then used throughout the entire forecast cycle for this time.

(3) The large-scale flow, (V_B,alpha), is taken as the analysed or forecast layer-averaged wind from 850-200mb, with the cyclone scales filtered out.

(4) Assumed values for x and gamma, along with the data found in steps (2) and (3), are fed into equations (1) and (2) and a forecast is produced. The large-scale flow is re-evaluated every 6 hours, using the prognosis fields, to incorporate the effects of synoptic changes.

This parameterized, linear model has been demonstrated to perform creditably, with control run errors in the Australian region better than the combined average errors for all objective aids out to 24 hours, while still remaining competitive to 36 hours (Table 1). Initial indications from the Northwest Pacific are also encouraging (Table 1). In this region, significant problems still remain with the method of separating the cyclone and the surrounding weather system scales, as required in step (3) of the forecast cycle. These are the focus of current research.

We consider that PTCM87 can provide a quick, versatile, microcomputer based forecast technique for tropical cyclone motion. The method also forms the basis for ongoing development of an objective decision tree forecast procedure and as a 'forecast game' training aid.

TABLE 1
Error statistics for test runs of PTCM87 in the Australian and Northwe[st] Pacific regions.

CYCLONE	12hr ERROR(km)	24hr ERROR(km)	REGION
Emma	121.1(18)	243.4(17)	Aust.
Ferdinand	126.9(5)	181.4(4)	Aust.
Frank	61.0 (16)	118.8(15)	Aust.
Gertie	104.0(16)	217.6(15)	Aust.
Gretel	141.7(4)	344.3(3)	Aust.
Irma	98.7 (2)	341.4(1)	Aust.
Jason	80.1 (9)	167.8(8)	Aust.
Jim	129.5(5)	215.2(4)	Aust.
Kathy	91.1 (11)	188.2(10)	Aust.
Sandy	84.2 (7)	175.7(6)	Aust.
Thelma	119.7(14)	245.6(13)	NW Pac.
MEAN	101.4(107)	204.4(96)	BOTH

SUMMARY OF WM. M. GRAY'S ONR SPONSORED TROPICAL CYCLONE MOTION RESEARCH AND FUTURE PLANS

By

William M. Gray

The author and his project personnel have been performing a variety of Tropical Cyclone (TC) motion related research. Our basic research purpose, in line with the ONR research mission, is to try to increase our general knowledge and understanding of the theory of TC motion. This research consists of a careful analysis of: 1) TC motion vs. the cyclone's steering current at various radii, 2) the physical process which best distinguish TC recurvature from nonrecurvature as measured by rawinsonde, aircraft, and digitized satellite data, 3) TC inner core (0-2 1/2° radius) steering motion as measured by 700 mb aircraft data, and 4) the impact of aircraft reconnaissance of TC initial position and conservative motion vector for input into TC motion forecasts.

A full description of the author's research is given in a 121 page write-up entitled "Tropical Cyclone Motion Research-Observation and Physical Implications" by W. Gray et al. (1988) with accompanying 150 pages of TC motion data as an appendix. This report was handed out at the ONR sponsored Rainbow Beach, Australia meeting of 29 June-1 July 1988.

The following is a brief summary of these research results.

With Regards to the Theory of TC Motion. We find that there is an interior 1-3° radius steering flow component which can be systematically different than the mean 5-7° TC steering wind or of the TC motion vector itself. The author believes that this is a result of the varying asymmetric inflow and outflow which occurs with moving tropical cyclones. We best isolate these varying radius steering influences for west-northwest (WNW) moving TCs from our 21-year rawinsonde composite analyses.

A careful look at these WNW moving TC's 1-3° radius 100-1000 mb or 300-850 mb deep layer mean winds show that they typically blow through the cyclone from rear to front. The TC thus moves slower not faster than its interior 1-3° radius steering current. This is also verified for north moving cyclones. These observations are contrary to the measurement and now generally held notion that (for westerly and northerly moving cyclones) TCs move faster than their steering current. This is true of the 5-7° surrounding mean steering current. It appears not to be true for the interior 1-3° radius TC steering current, however.

There can be no doubt that the westerly moving TC has a substantially stronger inner (1-3° radius) steering current from that of the surrounding (5-7°, 1-7°, or 5-9°) deep layer mean steering flow in which it is embedded. For westward moving cyclones the interior 1-3° mean winds are substantially stronger from the east and from the north than the 5-7° radius winds. These stronger interior steering components are also found in a large number of our Atlantic and other NW Pacific rawinsonde composites.

If we accept the 5-7° radius as the region of the representative surrounding steering current we can (in the MOT or with the TC track motion vector removed from all winds system) ask how specifically different the zonal and meridional winds are in the radial belts of 1-3°, 3-5°, and 7-9° radius from the assumed baseline steering values of the 5-7° radius. We will present much new statistics on this.

4.1 Reasons for Stronger Inner-Core Blowthrough

The stronger inner region meridional wind blowthrough are likely a consequence of the larger low-level inflow on the poleward side and the upper tropospheric outflow to the equatorial side of these WNW moving cyclones. Because of the east to west basic steering current and the resulting south to north pressure gradient, this interior vortex inflow from the north and outflow to the south goes down the pressure gradient and generates enhanced inner vortex momentum. Such an inflow-outflow pattern occurring in a stagnant or non-steering flow environment would, because of the lack of a steering current, not generate such enhanced inner vortex winds. Many previous numerical models with a non-steering flow envir., or unrealistic vertical motion have, of course, yet to model this enhanced interior steering component.

It is likely that the relative azimuthal orientation of these low level inflow and high level outflow patterns are an important influence on the TC's faster interior steering current. This appears a consequence of the TC's larger scale steering flow environment. Without a steering current it is probable that these faster interior winds would not be present. There are likely favorable and unfavorable large-scale steering currents and azimuthally oriented inflow and outflow patterns which enhance or reduce the interior steering current relative to the large-scale steering. If the TC's interior vortex (1-3° radius) inflow-outflow goes down the basic steering current pressure gradient then inner vortex wind enhancement will occur. If it goes up the gradient it will weaken the interior vortex steering current.

Figure 1 expresses this idea. Here the westward moving TC moves at an intermediate velocity and direction between the 1-3° and 5-7° radius flow patterns.

It is to be expected that the moving TC would advance slower and to the right of the 1-3° steering wind due to the strong surface frictional influences upon the inner-core (0-1°) vortex as compared to the 1-3° radius steering flow. As friction goes up with the square or cube of the wind speed, a strong inner radius clockwise rotating frictional influence is to be expected. The strong 0-1° clockwise rotating frictional influence would tend to drive the inner-vortex to the right of the 1-3° steering flow as is observed. The stronger inner core friction would also act to slow the inner vortex relative to the 1-3° radius wind.

The motion of the cyclone to the left and faster than the 5-7° steering is believed to be a result of the combination of stronger inner-core 1-3° steering and the Beta-gyre influences.

This is a new way of looking at TC motion. Beta-gyre are only part of the explanation of why the TC moves at a velocity different than their 5-7° steering flow.

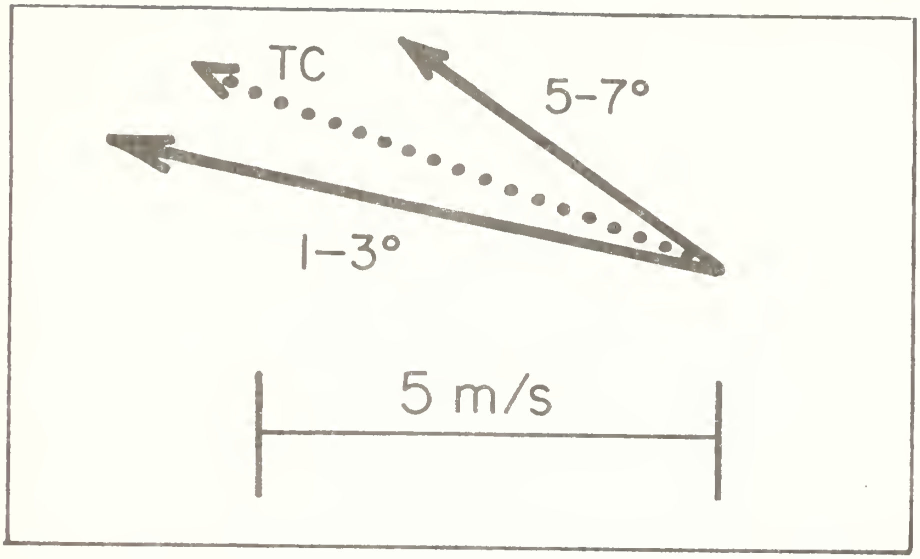


Fig. 1. Composite 800-300 mb mean 1-3° and 5-7° steering wind vectors for all west-northwest moving in the NW Pacific for a 21-year period. TC indicates the motion vector. Note that TC motion is slower and to the right of the 1-3° radius motion vector but to the left and faster than the 5-7° radius vector.

<u>With Regards to TC Recurvature vs. Non-recurvature</u>. We find that the major distinguishing factors between these two motion conditions 1-3 days before recurvature are found on the north side of the cyclone (this is well known) but in the very upper troposphere and lower stratosphere. The high level aspects of recurvature has been less appreciated. Recurvature does not occur until upper-tropospheric outflow is altered from a typical southwesterly direction to a more northwest to northeast direction. Cyclones appear to follow their upper tropospheric outflow patterns. Upper tropospheric information is much more of a distinguishing factor than 500 and 700 mb level data - which have been more commonly used in the past.

<u>With Regards to Other TC Motion Topics</u>. We find that between 0-2 1/2° radius 700 mb relative winds typically blow through NW Pacific TCs from front to back while in the Atlantic the lower tropospheric flow is from back to front. This causes the TC's relative tangential wind right to left quadrant asymmetry to be negative in the Pacific but positive in the Atlantic. These differences are due to the variation in the typical vertical wind profiles in which the NW Pacific and West Atlantic TCs exist in.

We have also studied the influence of initial position uncertainty on TC forecasts and find that TC track forecasts beyond 24 hours are little influenced by initial position error. This has implication for the reconnaissance question.

ISOLATED VORTEX MOTION IN THE ADVANCED TROPICAL CYCLONE MODEL

Greg J. Holland[1]
Naval Postgraduate School, Monterey

and

Rich Hodur
Naval Environmental Prediction Research Facility, Monterey

In this study, we examine the motion of an isolated vortex in the ATCM to determine the relative contributions of latent heating and of baroclinic and barotropic processes. This work forms part of our overall research program aimed at utilising numerical model and real data to diagnose the mechanisms of tropical cyclone motion. We also expect that the results of this study will help with further improvements to the initialisation of tropical cyclones in the operational version of ATCM.

The ATCM version used here has 21 levels in the vertical, 80km resolution and a 5600x5600km spherical domain. At the horizontal boundaries, the parallel wind component is set to zero and the perpendicular component is advected out. Deep convection is a version of the Anthes/Kuo parameterisation and shallow convection is parameterised by a vertical diffusion equation. The ECMWF boundary layer is used. The initial vortex is centred at 20°N with a maximum wind radius of 160km and a horizontal structure defined by the method of Holland (1980). A climatological vertical shear is added to change the vortex from a low level cyclone to an upper level anticyclone and the model is integrated for 96 hours.

The vortex propagated consistently northwestward during the integration period, in agreement with previous studies (Elsberry, 1988). The boundary layer and a weak secondary circulation developed during the first 24 hours. An abrupt commencement of core region latent heat release occurred near 36 hours, followed by establishment of an outflow regime. The centre also began to oscillate around the mean track as convective elements developed and orbited around the core region. The effects of this the core region latent heating were investigated by a second model run in which the precipitation was turned off at 36 hours.

---

[1]Permanent affiliation, Bureau of Meteorology Research Centre, Melbourne, Australia.

The following conclusions have been reached:

1. The northwestward propagation was largely a result of barotropic processes in the surface to 300mb layer. Any combination of layers between these levels contained an asymmetric beta-gyre pattern similar to that described by Fiorino and Elsberry (1988).

2. The outflow layer developed substantial asymmetries in response to the detrainment of mass and momentum from the core convection. These asymmetries were not of the typical beta-gyre pattern and seemed to have no direct effect on the vortex motion. We have yet to investigate possible indirect, or nonlinear interactions between this outflow regime and the cyclone motion.

3. The release of latent heat in the core region caused the vortex to propagate more poleward. We consider that this resulted from the increased convergence below 300mb as discussed by Holland (1983). This convergence also gradually strengthened the outer region circulation with a resulting slow evolution of the vortex motion to a more westward direction.

Vortex Motion on a Beta Plane

Lloyd J. Shapiro
Hurricane Research Division/ AOML
4301 Rickenbacker Causeway
Miami, FL 33149

A set of idealized experiments has been designed to investigate the influence of divergence and advective nonlinearities on hurricane motion and asymmetries due to the beta effect. A one-layer, shallow water (barotropic, primitive equation) numerical model was used on a beta plane. The multi-nested model was developed by K. V. Ooyama, based on the spectral application of a finite element representation. Comparison was made with solutions from a non-divergent form of the model. The effect of divergence and total Relative Angular Momentum (RAM) on vortex motion and evolution were evaluated.

For a shallow water depth of 1 km, corresponding to the equivalent depth of the first internal vertical mode, the Rossby radius of deformation is ~2000 km. By use of a Bessel function representation, the dominant spatial scale for a typical hurricane vortex is found to be ~250 km, which is much less than the Rossby radius. Scaling of the vorticity equation then indicates that divergence should have a very small effect on hurricane motion. Numerical experiments with initial symmetric vorticies confirm that the vortex track is essentially unaffected by divergence, with only a 4% difference in total displacement after 72 h between the non-divergent simulation and those with shallow water depths of 1 or 4 km. This result contradicts previous published studies on the effect of divergence. A feature of interest in the solutions is a very weak divergence quadrupole at the radius of maximum wind, oriented with convergence east and west of the axis. Although the direct effect of this local quadrupole on vortex motion is negligible, its long-term effect on vortex evolution, particularly in a more complete model with convective feedback, could be important.

The symmetric vortex develops asymmetries that have an influence far from the initial circulation. The asymmetries extend in all directions, but the strongest are associated with a series of alternating anticyclonic/cyclonic gyres that extend behind the vortex to the southeast. When the initial symmetric vortex is modified so as to have zero net RAM, the developing asymmetries are quite substantially reduced in strength. As proven by Flierl, Stern and Whitehead (1983, Dynamics of Atmospheres and Oceans, 7, 233-263), "...any slowly varying...and isolated disturbance on the beta plane must have zero net angular momentum...". If the initial vortex does not satisfy this condition, then it radiates Rossby waves. If the net RAM of the initial symmetric vortex is zero, no Rossby wave radiation field is produced, and the vortex remains isolated. Analyses indicate that the development of the alternating gyres behind the vortex with non-zero initial net RAM cause the total RAM to oscillate about zero. It appears that the Rossby waves tend to adjust the RAM, unsuccessfully, toward zero. In order to minimize the remote influence of the adjusting vortex, these results suggest that the initial symmetric hurricane vortex should be "isolated", with the total RAM constrained to be near zero. For an initially asymmetric vortex there are similar additional constraints related to torque. These ideas need to be confirmed and extended with further experiments and analysis.

Tropical Cyclone Motion Forecasting and the Adjoint Method of Data Assimilation

by

Wayne H. Schubert
Gerald D. Taylor
Colorado State University

1. Introduction

Suppose we are trying to make a tropical cyclone motion forecast using a dynamical model. The dynamical model could be of any level of complexity—from the nondivergent barotropic model, through the divergent barotropic model, to the fully three dimensional primitive equations with parameterized moist physics. No matter how simple or complex the model, we are faced with the problem of model initialization based on sparse observations. Observations in the tropical cyclone are often totally lacking, and thus the vortex is essentially unresolved. We are fortunate if there are even enough observations to adequately define the larger scale "steering flow." Under such circumstances, initialization often involves insertion of a "bogus vortex." The dynamical model sometimes moves this vortex in a direction and at a speed quite different from the observed. The track forecast might be improved by changing certain structure parameters of the bogus vortex, e.g. its size, strength or tangential asymmetry. However, such procedures remain somewhat arbitrary.

The procedure described in the preceeding paragraph makes no use of mass, wind or track data prior to the initialization time. Now, let us look at the problem using the concept of four dimensional data assimilation, and, in particular, the adjoint method, which results in specifying complete initial conditions at a given instant from observations distributed in space and time. Suppose we have acquired (over the time interval $t_0 \leq t \leq t_1$) large-scale wind and temperature data from scattered island radiosonde stations and a sequence of tropical cyclone position fixes from satellite data. If we are forecasting with the nondivergent barotropic model we need only consider the vorticity field. Then assume that the cyclone tracks can be somehow converted to "vorticity observations" so that we have $\zeta_{obs}(\lambda, \mu, t)$ for $t_0 \leq t \leq t_1$, where λ is longitude and μ is the sine of latitude. A model forecast from time t_0 with initial condition $\zeta_0(\lambda, \mu)$ produces the field $\zeta(\lambda, \mu, t)$. Let J be some integral (spatial and temporal) measure of the squared difference between $\zeta(\lambda, \mu, t)$ and $\zeta_{obs}(\lambda, \mu, t)$. Since $\zeta_{obs}(\lambda, \mu, t)$ is known and $\zeta(\lambda, \mu, t)$ is determined from $\zeta_0(\lambda, \mu)$ by model integration, the "distance function" J depends only on $\zeta_0(\lambda, \mu)$. How can we vary the $\zeta_0(\lambda, \mu)$ field to make J as small as possible? Stated differently, how can we massage the data at t_0 in order to make the model track fit closely with the observed track over the interval $t_0 \leq t \leq t_1$? If we could do this we would have a model field close to the observed field over the interval $t_0 \leq t \leq t_1$, and intuition would suggest that continuation of this model solution past t_1 would give a pretty good track. At the very least, the model vortex should be going the right direction and speed at t_1.

Let us try to minimize J in a naive and brute force fashion. Consider a discretized model with N^2 degrees of freedom (N by N points, say, where $N \sim 256$). Thus $\zeta_0(\lambda, \mu)$ is represented by a vector $\boldsymbol{\zeta}_0$ of length N^2. Let $\nabla_{\boldsymbol{\zeta}_0} J$ denote the gradient of J with respect to each element of $\boldsymbol{\zeta}_0$, which means $\nabla_{\boldsymbol{\zeta}_0} J$ is a vector of length N^2. The first element of $\nabla_{\boldsymbol{\zeta}_0} J$ tells us how the distance function J would be changed if we modified the initial condition at the first point in the grid, and so on through all the points of the grid. Thus, if we know $\nabla_{\varsigma_0} J$, we could make simultaneous, subtle modifications of ς_0 at all points in order to reduce J. We conclude that knowldege of $\nabla_{\varsigma_0} J$ might give us considerable power to improve track forecasts. The brute force method of determining $\nabla_{\varsigma_0} J$ consists of making a forecast using ς_0 as initial condition, followed by N^2 more forecasts with ς_0 slightly modified in turn at each grid point; each of the N^2 forecasts is compared to the original forecast and the associated change in J calculated. Unfortunately, the apparent necessity of making thousands of model runs would probably render the forecast untimely (what's additionally troublesome is that the above procedure has to be iterated).

But here comes the adjoint method to the rescue. The adjoint method can give us $\nabla_{\varsigma_0} J$ in a time equivalent to only a few model forecast runs. This is a powerful result, and here is all we need to do. Derive the tangent linear equation, which in our case is the nondivergent barotropic vorticity equation linearized about the present model solution $\varsigma(\lambda, \mu, t)$. Then, find the adjoint of the tangent linear equation. Finally, run the original nonlinear model forward in time from t_0 to t_1, and then the adjoint model backwards in time from t_1 to t_0. If this is done in the proper fashion, the output is $\nabla_{\varsigma_0} J$, which can be used to modify ς_0 and give a better track simulation. The ς_0 field can be iteratively modified in this fashion. Since the adjoint model takes about the same computer time as the forecast model, each iteration is roughly equivalent to two forecast runs, and a typical five iteration procedure is equivalent to ten forecast runs.

2. Derivation of the adjoint of the vorticity equation

Consider nondivergent barotropic motion on the sphere. Such flow is governed by

$$\frac{\partial \varsigma}{\partial t} + \frac{1}{a^2} \frac{\partial (\psi, 2\Omega\mu + \varsigma)}{\partial (\lambda, \mu)} = 0, \tag{2.1}$$

$$\varsigma = \frac{1}{a^2} \left\{ \frac{1}{(1-\mu^2)} \frac{\partial^2 \psi}{\partial \lambda^2} + \frac{\partial}{\partial \mu} \left[\left(1 - \mu^2\right) \frac{\partial \psi}{\partial \mu} \right] \right\}, \tag{2.2}$$

where λ is the longitude, μ the sine of the latitude, a the radius of the earth, and Ω the angular velocity of rotation of the earth.

If ς and $\varsigma + \delta\varsigma$ are two solutions of (2.1)–(2.2), the governing equation for $\delta\varsigma$ is

$$\frac{\partial \delta\varsigma}{\partial t} = \frac{\partial (\varsigma + \delta\varsigma)}{\partial t} - \frac{\partial \varsigma}{\partial t} = \frac{1}{a^2} \left\{ \frac{\partial (2\Omega\mu + \varsigma + \delta\varsigma, \psi + \delta\psi)}{\partial (\lambda, \mu)} - \frac{\partial (2\Omega\mu + \varsigma, \psi)}{\partial (\lambda, \mu)} \right\}. \tag{2.3}$$

Linearizing about the solution ς we obtain

$$\frac{\partial \delta\varsigma}{\partial t} = \frac{1}{a^2} \left\{ \frac{\partial (2\Omega\mu + \varsigma, \delta\psi)}{\partial (\lambda, \mu)} + \frac{\partial (\delta\varsigma, \psi)}{\partial (\lambda, \mu)} \right\}, \tag{2.4}$$

which is called the tangent linear equation. Now define the inner product of two vorticity fields ς and ς' as

$$\langle \varsigma, \varsigma' \rangle = \iint \nabla\psi \cdot \nabla\psi' d\lambda d\mu \tag{2.5}$$

we can show that the Laplacian operator is self-adjoint, i.e.

$$\langle \psi, \varsigma' \rangle = \langle \varsigma, \psi' \rangle. \tag{2.6}$$

After some manipulation we can show that the adjoint of (2.4) is

$$\frac{\partial \delta' \varsigma}{\partial t} = \nabla^2 \frac{\partial (\delta'\psi, \psi)}{\partial (\lambda, \mu)} + \frac{\partial (2\Omega\mu + \varsigma, \delta'\psi)}{\partial (\lambda, \mu)}. \tag{2.7}$$

3. Concluding remarks

There are many questions to be explored.

- To what extent can the adjoint method reconstruct smaller scale features that are below the resolution of the observations? If the tangential asymmetries of the vortex are an important cause of a certain track, one might expect that forcing the model to produce this track could lead to reconstruction of some of this asymmetry.

- To what extent are moist convection, surface friction and vertical structure important for accurate tropical cyclone motion prediction? This might eventually be answered by running a tropical cyclone simulation with a model containing "complete physics." Regard a certain time interval of this output as data. Now remove a certain piece of the physics (moist convection, say) and use the simplified model (and its adjoint) to assimilate data from the original model. After the data is assimilated, make a forecast of the cyclone motion and compare it to the motion in the complete physics model.

References

Courtier, P., and O. Talagrand, 1987: Variational assimilation of meteorological observations with the adjoint vorticity equation. II: Numerical results. *Quart. J. Roy. Meteor. Soc.*, **113**, 1329–1347.

Talagrand, O., and P. Courtier, 1987: Variational assimilation of meteorological observations with the adjoint vorticity equation. I: Theory. *Quart. J. Roy. Meteor. Soc.*, **113**, 1311–1328.

TROPICAL CYCLONE MOTION STUDIES
JULY 1988

Roger K. Smith (Principal Investigator)
GFD Laboratory, Monash University, and
Meteorological Institute, University of Munich.

and

Wolfgang Ulrich
Meteorological Institute, University of Munich.

Our research to date has focused on three problems. The first is an extension of the numerical model simulations initiated by Chang and Williams (1987) and continued by Fiorino (1987). We have developed a similar non–divergent, barotropic, finite–difference model to theirs, and have used the vorticity–streamfunction formulation in a β–plane channel. The model differences are relatively minor: we chose to use the Adams–Bashforth time integration scheme as opposed to leap frog and have implemented the Arakawa conserving form of the Jacobian to conserve absolute enstrophy as opposed to relative enstrophy. In some early tests of the model, the evolution of the vortex asymmetry during the first two time steps was compared with the analytical tendencies calculated by Adem's method (Adem, 1956). It was found that, with a horizontal grid resolution (Δx) of 20 km and a vortex with a radius of maximum wind (r_{max}) of 76 km, the numerically predicted vorticity tendencies $\partial\zeta/\partial t$ and $\partial^2\zeta/\partial t^2$ were severely affected by truncation error, while the corresponding streamfunction tendencies lacked the intrinsic symmetry of the analytical solutions. The discrepancies were found to be entirely due to inadequate numerical resolution in the model (see Fig.1). Fiorino (1987) found that for an initial vortex with $r_{max} = 100$ km on a beta plane at rest, the subsequent 72 hr drift could be adequately predicted using $\Delta x = 40$ km. Be this as it may, our findings suggest that in order to accurately predict the development of the vorticity field, at least on the scale of $1 - 2\ r_{max}$, a much smaller Δx must be used. Since the thrust of our own research is to understand the details of vortex evolution from the scale of the beta gyres down to the core scale r_{max}, we have chosen to use a much higher resolution (typically $\Delta x \sim 10$ km) at the expense of using a smaller domain size than Fiorino (i.e. 2000 km × 2000 km compared with 4000 km × 4000 km; Fiorino also implemented a movable grid for extended time integrations).

While Fiorino has concentrated on the evolution of the streamfunction fields alone, we have examined the evolution of asymmetries in the vorticity field as well. Moreover, we have used a method of partitioning suggested by Kasahara and Platzman (1963) (their Method III) as a basis for interpretations. Diagnostic analyses of the solutions are continuing.

Motion of initially asymmetric vortices

In a second series of calculations we have studied the motion of initially asymmetric vortices, both on an f–plane and on a beta–plane, to develop insight into the possible effects on tropical cyclone motion on the development of internal asymmetries such as those associated with new convective bands. The problem is relevant also to the design of more appropriate bogus vortices for insertion into forecast models. It is evident from calculations of the type described above, where an initially *symmetric* vortex on a beta plane acquires motion and distorts even in the absence of a basic flow, that more subtle forms of bogus vortices are required to ensure that the previous observed speed and direction of motion of a real cyclone are preserved following initialization in a numerical forecast model.

Some results of the calculations are shown in Figs.2–5. Figure 2 compares the evolution of the vorticity fields in two experiments on an f–plane where the initial vortex has a wavenumber one asymmetry aligned along the x–(east–west) axis, the positive anomaly being to the east of the vortex centre. In the first experiment, the maximum in the anomaly is at the radius of maximum wind of the symmetric vortex; in the second it is at a larger radius ($\sqrt{2}\ r_{max}$), the magnitudes of the anomalies being the same. In both cases the vortices track initially towards the south as would be inferred from the orientation of the asymmetry. However, in the former case, the vortex centre moves only a relatively short distance (of order 60 km) and stalls (Fig.3a), by which stage, after only 12 hours, the asymmetry has been largely wound up by the strong shearing motion in the vortex core (Fig.2c). In the latter case, the initial asymmetry is located outside the radius of maximum winds where the shearing effect is much slower (cf. Figs.2c and 2d). Accordingly, the vortex continues to move and after 12 hours it has become displaced about 250 km southeast of its initial position (Fig.3b). This southeastward motion persists and at 60 hours the displacement is 560 km. Our present challenge is to understand, *inter alia*, the reason for the steady southeasterly track. When a beta effect is included, both vortices end up tracking northwestwards; for the broader asymmetry the change in track direction takes place after about 24 hours (Fig.3c). These results suggest that while asymmetries within the core may have little effect on the track as they are rapidly destroyed by shear, while those beyond the radius of maximum wind, even on the scale of $2r_{max}$, can have an appreciable effect on motion.

The case of a strong vortex–weak vortex interaction may be considered as a case of an extreme asymmetry. Figure 4 shows the evolution of the vorticity and streamfunction fields in a case in point. After 15 hours, the weak vortex has been wound into a spiral arm of the strong vortex by the shearing effect of the stronger circulation of the latter. As in the previous cases, the strong vortex tracks initially southwards, but on a beta–plane the track ultimately turns northwestwards; on a f–plane, the vortex stalls after a relatively short displacement to the southeast (Fig.5). Similar calculations have been reported recently by Wang and Zhu (1988).

Vortex–planetary wave interactions

Finally we are studying the interaction of vortices in a model where there are large–scale spatial and temporal variations of the absolute vorticity gradient. Such variations are obtained by embedding the initial vortex in stationary or propagating large–scale and finite amplitude Rossby waves in a zonal channel. By locating the initial vortex in the easterly flow, south of the anticyclone centre (northern hemisphere!), we are in a position to study the dynamics of recurvature. Our plan also is to study the evolution in the orientation of the so–called beta gyres as the local, large–scale absolute vorticity gradient changes. In addition we aim to explore the possibility of parameterizing the vortex motion in terms of the large–scale steering current provided by the Rossby wave, together with a drift which depends, *inter alia*, on the magnitude and direction of the absolute vorticity gradient, as well as the vortex size.

References

Adem, J., 1956: A series solution for the barotropic vorticity equation and its application in the study of atmospheric vortices. *Tellus*, 8, 364–372.

Chan, J.C. and R.T. Williams, 1987: Analytical and numerical studies of the beta–effect in tropical cyclone motion. Part I: Zero mean flow. *J. Atmos. Sci.*, 44, 1257–1265.

Fiorino, M., 1987: The role of vortex structure in tropical cyclone motion. Ph.D. Thesis, Naval Postgraduate School, Monterey, pp.370.

Kasahara, A., and G.W. Platzman, 1963: Interaction of a hurricane with a steering field and its effect upon the hurricane trajectory. *Tellus*, 15, 321–335.

Wang, Y. and Y. Zhu, 1988: A numerical study of the Fujiwhara effect of two interacting cyclonic vortices (to be published).

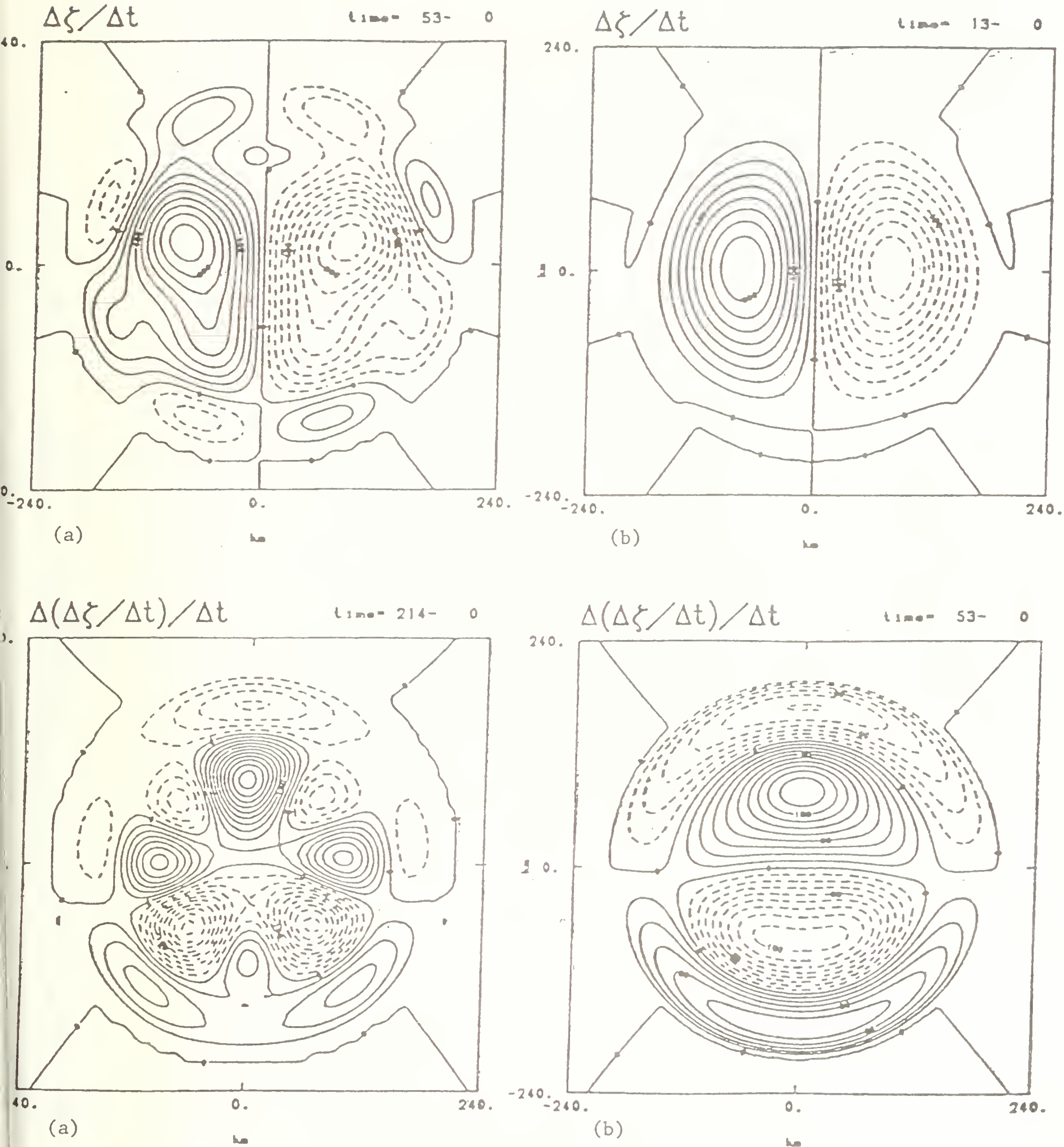


Figure 1 Initial first and second order vorticity tendency patterns for the motion of Adem's vortex on a beta plane: (a) model, $\Delta x = 20$ km; (b) model, $\Delta x = 5$ km. The latter is virtually identical with the analytic solution.

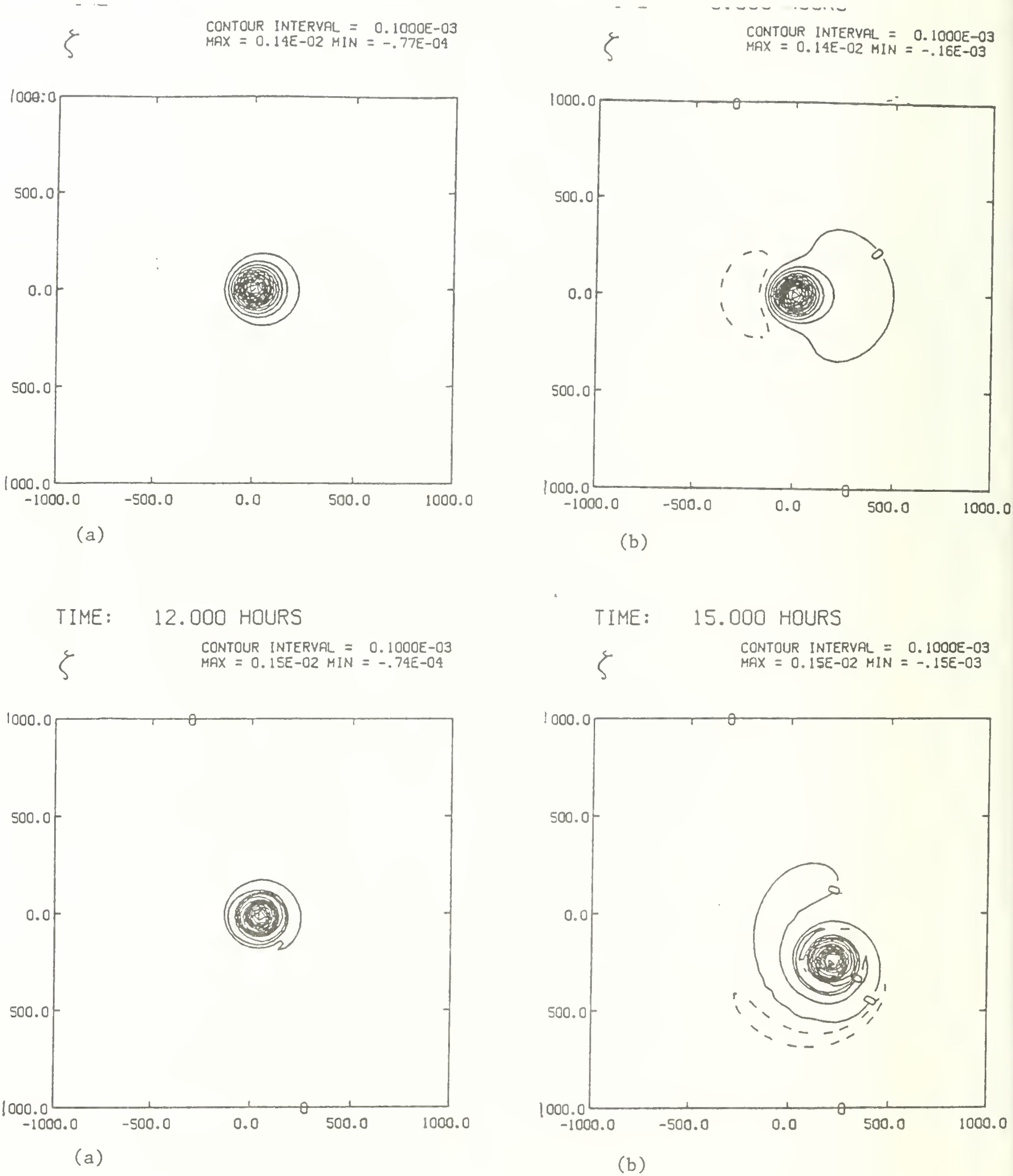


Figure 2 Vorticity isopleths showing the evolution of slightly asymmetric vortices on an f–plane: (a) vorticity anomaly a maximum at the radius of maximum (mean) tangential wind, r_{max}; (b) vorticity anomaly maximized at $\sqrt{2}r_{max}$.

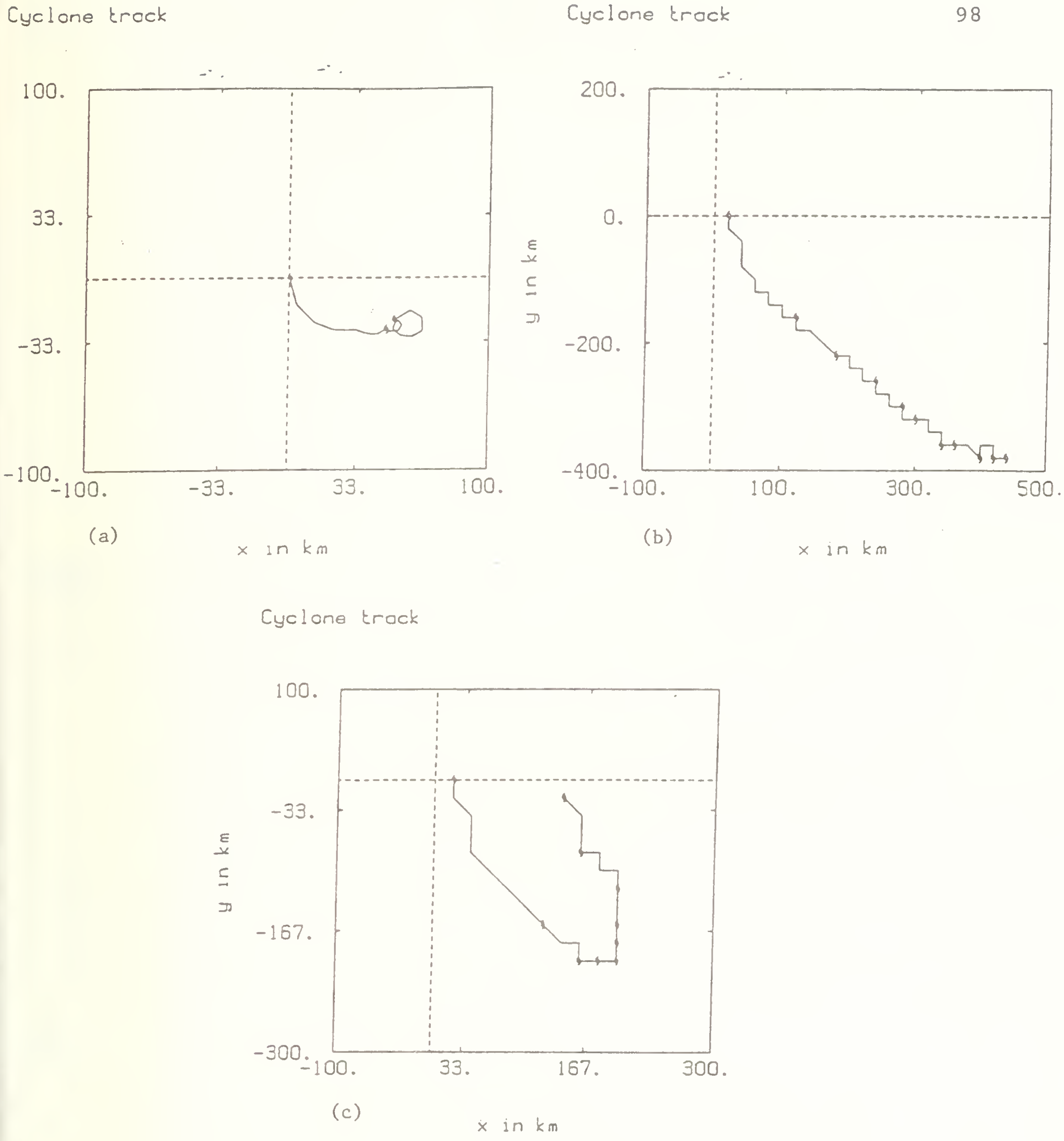


Figure 3 Vortex tracks corresponding to the simulations in Fig.2. (a), (b) corresponding with the vortices in Fig.2a, 2b, respectively. (c) is for the broader asymmetry (Fig.2b) on a beta plane. The cyclone symbols represent six–hourly vortex positions.

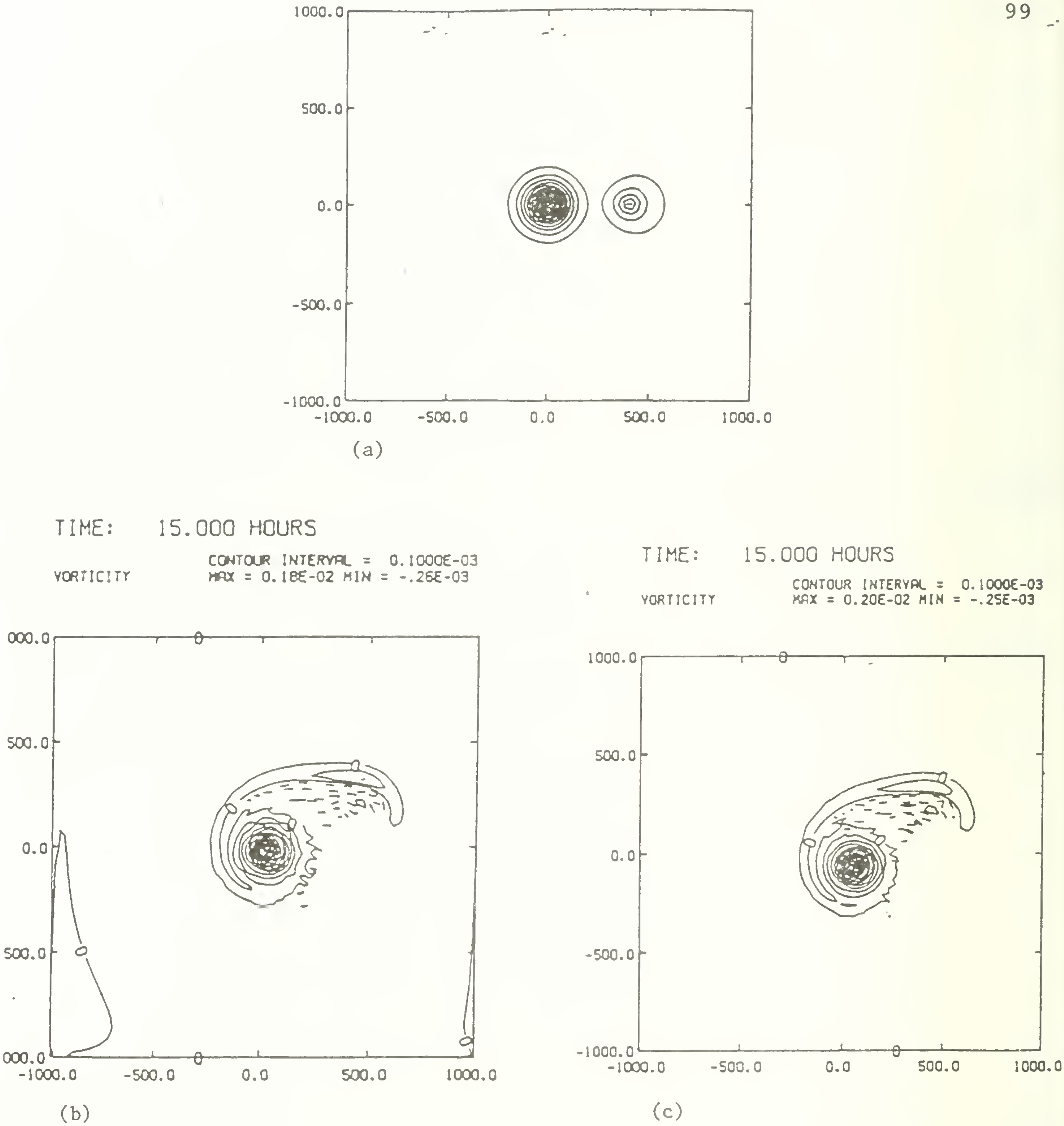
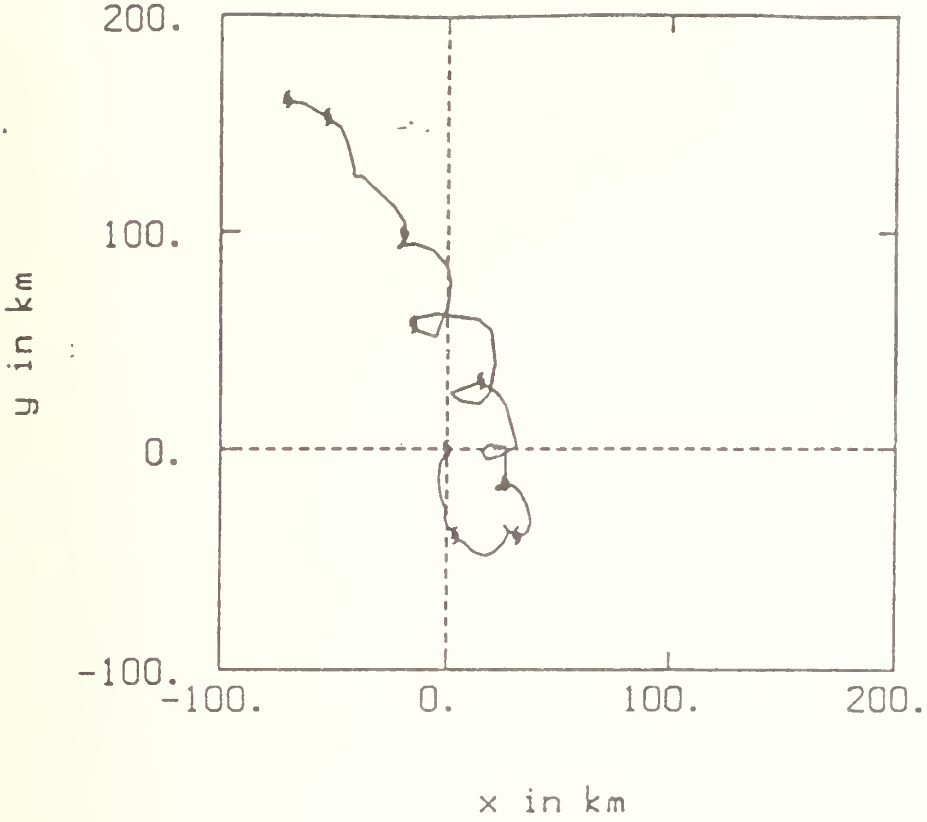
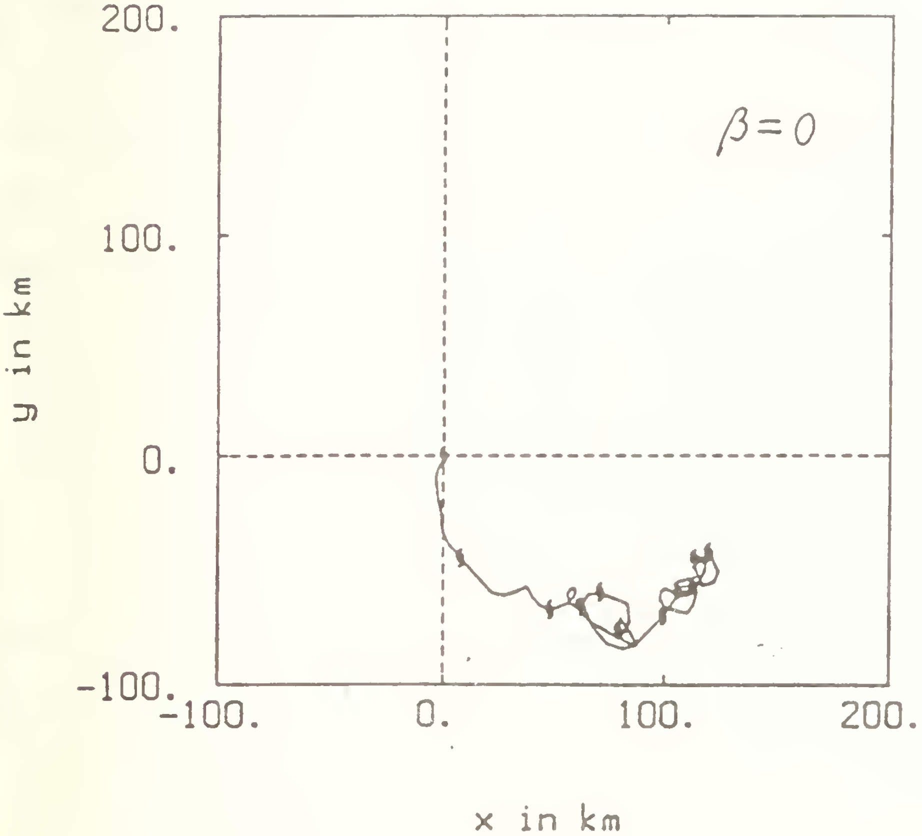


Figure 4 Vorticity distributions for a strong vortex–weak vortex interaction, an example of an extreme asymmetry. (a) initial field; (b) field after 15 hours when $\beta \neq 0$; (c) field after 15 hours when $\beta = 0$.



(a)



(b)

Figure 5 Vortex tracks corresponding with the simulations in Fig.4. (a) $\beta \neq 0$; (b) $\beta = 0$. The cyclone symbols represent six–hourly vortex positions.

Dynamics of the vortex structure on the beta-plane

R. T. Williams and Melinda S. Peng

The asymmetric structure of a vortex moving on the beta-plane is studied using the barotropic vorticity equation which is linearized with respect to the symmetric part of the vortex. The total system is transformed to a coordinate system moving with the vortex. The direction and speed of the movement is specified from the guidence of the full nonlinear model results. The asymmetric part of the vortex is given by the solution to the linearized vorticity equation. A sign change in the vorticity gradient of the basic state leads to different inner and outer structures for wavenumber one. For the steady-state solution, the inner part is oriented in the northeast direction unless the speed of the translation is substantially large. The outer part corresponds very well to the beta-gyre obtained in the numerical model. Since this outer gyre is oriented along the specified track, the model is capable of describing the dynamics leading to the structure of beta-gyre. The inner gyre is centered on the radius of maximum wind and the intensity is much larger than the outer beta-gyre. The outer beta-gyre is isolated by putting a wall a few grid points away the inner boundary so that the inner gyre cannot overwhelm the outer gyre. The time-dependent analytical solution then simulates the solutions of the numerical model in the earlier stages.

More About Linear Vortex Motion

H.E. Willoughby
(HRD/NOAA, Miami, FL)

Calculations with a quasi-analytical linear model of a moving, hurricane-like barotropic vortex (Willoughby, 1988) showed that a vortex with cyclonic flow throughout exhibited unphysically fast poleward motion on a beta plane. Anticylonic flow introduced at the periphery of the vortex reduced the poleward speed because the net coriolis force acting on the air in the vortex was proportional to the relative angular momentum (RAM) of the axisymmetric flow. Further calculations indicate that the wave flux of angular momentum due to the asymmetric perturbation induced at zero frequency by the beta effect acts to adjust the axisymmetric RAM toward zero. The excessive poleward motion arose because the perturbation at zero frequency is a normal mode of the vortex, as is the perturbation at the most anticyclonic orbital frequency of a vortex in which anticylonic flow far from the center makes the RAM small. When the vortex is cyclonic throughout, three normal modes have zero frequency: a stable mode and a conjugate pair of barotropically unstable modes with e-folding time of about 75 days. When the mean vortex has small RAM, only the stable normal mode remains at zero frequency while the unstable modes move to the most anticyclonic orbital frequency and their growth rate increases by an order of magnitude. In both cases, the unstable modes grow so slowly that the normal modes' importance lies in resonance at a particular frequency rather than in stability or instability.

Reference

Willoughby, H. E., 1988: Linear motion of a shallow water, barotropic vortex. J. Atmos. Sci., 45, 1906-1928.

INITIAL DISTRIBUTION LIST

Dr. Robert Abbey
ONR (Marine Meteorology)
Arlington, VA 22217

Dr. Alan Weinstein
ONR (Ocean Science Division)
Arlington, VA 22217

Dr. Robert T. Merrill
Space Science & Engineering Center
1225 W. Dayton Street
Madison, WI 53706

Dr. Mark DeMaria
Hurricane Research Division
AOML/NOAA
4301 Rickenbacker Causeway
Miami, FL 33149

Professor T. N. Krishnamurti
Department of Meteorology
Florida State University
Tallahassee, FL 32312

Dr. Greg Holland
Bureau of Meteorology Research Centre
P. O. Box 1289K
Melbourne, Victoria 3001
Australia

Dr. John McBride
Bureau of Meteorology Research Centre
P. O. Box 1289K
Melbourne, Victoria 3001
Australia

Dr. Tom Keenan
Bureau of Meteorology Research Center
P. O. Box 1289K
Melbourne, Victoria 3001
Australia

Dr. Roger Smith
Department of Mathematics
Monash University
Clayton, Victoria 3168
Australia

Dr. Hugh Willoughby
Hurricane Research Division
AOML/NOAA
4301 Rickenbacker Causeway
Miami, FL 33149

Dr. Bill Frank
Department of Meteorology
503 Walker Building
Pennsylvania State University
University Park, PA 16802

Professor Bill Gray
Atmospheric Science Department
Colorado State University
Fort Collins, CO 80523

Dr. Joe Chi
Department of Civil & Mechanical Engineering
University of the District of Columbia
4200 Connecticut Avenue, NW
Washington, DC 20008

Dr. R. Anthes
NCAR
P. O. Box 3000
Boulder, CO 80307

Dr. Y. Kurihara
Geophysical Fluid Dynamics Lab
Princeton University
P. O. Box 308
Princeton, NJ 08542

Dr. Makut B. Mathur
National Meteorological Center
Washington, DC 20233

Dr. Simon Chang
Naval Research Lab
Washington, DC 20233

Dr. Robert Tuleya
Geophysical Fluid Dynamics Lab
Princeton University
P. O. Box 308
Princeton, NU 08542

Keqin Dong
State Meteorological Administration
Western Suburb
Beijing
People's Republic of China

Mr. J. Jarrell
SAIC
205 Montecito Avenue
Monterey, CA 93940

Professor George Chen
Department of Atmospheric Science
National Taiwan University
Taipei, Taiwan

Dr. Mike Fiorino
Evans Communications, Inc.
P. O. Box 7400
Arlington, VA 22207

Dr. John Hovermale
NEPRF
Monterey, CA 93943

Dr. Ted Tsui
NEPRF
Monterey, CA 93943

Dr. R. Hodur
NEPRF
Monterey, CA 93943

Professor R. T. Williams
NPS
Monterey, CA 93943

Dr. M. Peng
NPS
Monterey, CA 93943

MAJ C. Holliday (USAF)
AFGWC - WFM
Offut AFB, NE 68113-5000

MAJ B. Columbus (USAF)
AFGWC - WFM
Offut AFB, NE 68113-5000

Dr. J. C.-L. Chan
Royal Observatory
134A Nathan Road
Kowloon
Hong Kong

Dr. Robert Burpee
Hurricane Research Division
AOML/NOAA
3401 Rickenbacker Causeway
Miami, FL 33149

Dr. Stanley Rosenthal
Hurricane Research Division
AOML/NOAA
3401 Rickenbacker Causeway
Miami, FL 33149

Dr. Peter Black
Hurricane Research Division
AOML/NOAA
4301 Rickenbacker Causeway
Miami, FL 33149

Dr. Steve Lord
Hurricane Research Division
AOML/NOAA
4301 Rickenbacker Causeway
Miami, FL 33149

Library (2)
NPS
Monterey, CA 93943

Defense Technical Information Center (2)
Cameron Station
Alexandria, VA 22314

Research Administration
NPS (Code 012)
Monterey, CA 93943

Catalino P. Arafiles
Philippine Atmospheric, Geophysical & Astronomical Service Administration
Asia Trust Building
1424 Quezon Avenue
Quezon City
Philippines

Takeo Kitade
Numerical Forecast Division
Japan Meteorological Agency
Otemachi 1-3-4, Chiyodaku
Tokyo, Japan 100

Masanori Yamasaki
Meteorological Research
Institute
1-1 Nagamine, Yatabe
Tsukuba-gun, Ibaraki
Japan 305

Masaru Shimamura
Meteorological College
Asaki-cho, Kashima-shi
Chiba Prefecture Japan

Charles Neumann
National Hurricane Center
Gables No. 1 Tower, Rm 631
1320 S. Dixie Highway
Coral Gables, FL 33146

Chenglan Bao
Department of Atmospheric
Sciences
Nanjing University
Nanjing, Jiangsu Province
People's Republic of China

Hanliang Jin
Shanghai Typhoon Institute
166 Puxi Road
Shanghai
People's Republic of China

Lianshou Chen
Central Meteorological
Observatory
State Meteorological
Administration
Baishiqiaolu No. 46
Western Suburb, Beijing
People's Republic of China

Dr. Carl Friehe
Mechanical Engineering
University of California
at Irvine
Irvine, CA 92717

Dr. Ray Zehr
Cooperative Institute for
Research in the Atmosphere
Colorado State University
Fort Collins, CO 80523

Dr. John Lewis
NOAA/NSSL
Norman, OK 73019

Dr. Arthur Pike
National Hurricane Center
1320 S. Dixie Highway
Coral Gables, FL 33146

Dr. John Molinari
Earth Science Building, Rm 219
State University of New York
at Albany
Albany, NY 12222

Edwin Nunez
Nichols Research Corporation
4040 S. Memorial Parkway
Huntsville, AL 35802

Dr. G. D. Emmitt
Simpson Weather Associates
809 E. Jefferson Street
Charlottesville, VA 22902

Chris Velden
Space Science & Engineering
Center
1225 W. Dayton Street
Madison, WI 53706

Dr. C. Hayden
CIMMS
1225 W. Dayton Street
Madison, WI 53706

Professor T. Fujita
Department of Geophys. Sci.
University of Chicago
5734 S. Ellis Avenue
Chicago, IL 60637

Robert Sheets
NOAA/NHC
Gables No.1 Tower, Rm 631
1320 S. Dixie Highway
Coral Gables, FL 33146

Geoff Love
Bureau of Meteorology
P. O. Box 735
Darwin, New Territories
Australia 5794

Jim McFadden
NOAA/OAO
P. O. Box 020197
Miami, FL 33120

Dr. Ed Rodgers
Laboratory for Atmospheric Sciences
NASA-Goddard Space Flight Ctr.
Greenbelt, MD 20771

Siri Jodha Singh Khalsa
CIRES
University of Colorado
Campus Box 449
Boulder, CO 80309

LT COL C. P. Guard
HQ Air Weather Service (AWS/DNT)
Scott AFB, IL 62225-5008

CDR S. Sandgathe, USN
Chief of Naval Operations
OP-981-D
Navy Department
Washington, DC 20350-2000

Director,
Joint Typhoon Warning Center
COMNAVMARIANAS Box 17
FPO San Francisco, CA 96630

Dr. Frank Marks
HRD/AOML/NOAA
4301 Rickenbacker Causeway
Miami, FL 33149

Professor Colin Ramage
Department of Meteorology
University of Hawaii
2525 Correa Road
Honolulu, HI 96822

Vin Lally
NCAR
P. O. Box 3000
Boulder, CO 80307

James Franklin
HRD/AOML/NOAA
3401 Rickenbacker Causeway
Miami, FL 33149

Dr. Lloyd Shapiro
HRD/AOML/ NOAA
4301 Rickenbacker Causeway
Miami, FL 33149

Professor Duane Stevens
Department of Atmos. Science
Colorado State University
Fort Collins, CO 80523

CDR Tom Gerish
NOAA/OAO
P. O. Box 020197
Miami, FL 33120

Professor J. G. De Las Alas
Dept. of Met. and Ocgr.
University of the Philippines
Diliman, Quezon City 3004
Philippines

Professor Cheng-shang Lee
Department of Atmos. Science
National Taiwan University
Taipei, Taiwan
Republic of China

Dr. Wolfgang Ulrich
Meteorologisches Institut
Universitat Munchen
Theresienstr. 37
8000 Munchen 2
West Germany

Professor Jim Sadler
Department of Meteorology
University of Hawaii
2525 Correa Road
Honolulu, HI 96822

Mr. R. Falls
Regional Director
Bureau of Meteorology
GPO Box 413
Brisbane Qld 4001 Australia

Director, Typhoon Moderation
Research Office
PAGASA
1424 Quezon Avenue
Quezon City, Philippines

Coordinator,
Typhoon Committee
Secretariat
PAGASA
1424 Quezon Avenue
Quezon City, Philippines

Patrick Sham
Director, Royal Observatory
134A Nathan Road
Kowloon
Hong Kong

R. L. Southern
14 Leverburgh Street
Ardross 6153
Western Australia

Don Vickers
World Meteorological
Organization
41 Guissepe-Mota
Case Postale N^{o}. 5
CH-1211 Geneve 20
Switzerland

Dr. Ryozo Tatehira
Director, Forecast Dept.
Japan Meteorological Agency
Otemachi 1-3-4, Chiyodaku
Tokyo 100 Japan

Dr. Lim Joo Tick
Malaysian Meteorological
Service
Jalan Sultan
Petaling Jaya, Selangor
Malaysia

Luo Jibin
State Meteorological
Administration
Baishiqiaolu No. 46
Western Suburb, Beijing
People's Republic of China

Patipat Patvivatsiri, Ph.D.
Meteorological Department
612 Sukumvit Road
Bangkok 10110
Thailand

Eul Young Chun
Director-General, Forecast
Bureau
Korea Meteorological Service
1 Songwol-dong, Chongno-qu
Seoul 110, Korea

Professor Wayne Schubert
Department of Atmospheric
Sciences
Colorado State University
Fort Collins, CO 80523

Commanding Officer
1st WW
Hickam AFB, Hawaii 96853

Dr. Morton Glass
Meteorology Division
Air Force Geophysics Lab
Hanscom AFB, MA 01731

Chairman,
Department of Meteorology
Naval Postgraduate School
Monterey, CA 93943-5000

T. C. Yeh
Computer Center
Central Weather Bureau
64 Kung Yuan Road
Taipei, Taiwan 100
Republic of China

Professor Bruce Morton
Department of Mathematics
Monash University
Clayton, Victoria 3168
Australia

LT COL S. M. Horn, USAF
Commander, 20th Weather
Squadron
APO San Francisco, CA 96328

Martin Yerg
Chief, International
Affairs Branch
National Weather Service
Silver Spring, MD 20910

Professor T. Schroeder
Department of Meteorology
University of Hawaii
2525 Correa Road
Honolulu, HI 96822

Professor Zou Jingmeng
State Meteorological
Administration
Western Suburb
Beijing
People's Republic of China

R. H. Hagemeyer
NOAA/NWS Pacific Region
P. O. Box 50027
Honolulu, HI 96850

CAPT B. S. Cronyn, USN
USCINCPAC (J37)
Camp Smith, HI 96861

Commanding Officer
30th Weather Squadron\cc

C. B. H. Lee
Central Pacific Hurricane
Center
National Weather Service
Forecast Office
Honolulu, HI 96819

Director, Env. & Life Sci.
Office of Undersecretary of
Defense for Res & Eng E&LS
Rm. 3D129, The Pentagon
Washington, DC 20505

Professor T.Y. Tsay
Department of Atmospheric
Science
National Taiwan University
Taipei, Taiwan
Republic of China

Professor Ron Smith
Department of Geology
& Geophysics
Yale University
New Haven, CT 06511

Professor Zeng Quincun,
Director, Institute of
Atmospheric Physics
Academica Sinica
Beijing
People's Republic of China

Commanding Officer
Naval Western Oceanography
Box 113
Pearl Harbor, HI 96860-5050

Commander
Naval Oceanography Command
NSTL, MS 39529-5000

Commanding Officer
NAVOCEANCOMFAC Yokosuka
FPO Seattle, WA 98762

Commanding Officer
NAVOCEANCOMFAC Cubi Point
FPO San Francisco, CA 96654

COMTHRIDFLT
ATTN: NSAP Science Advisor
Pearl Harbor, HI 96860-7500

Federal Coord. for Meteor.
Servs & Sup Resh. (OFCM)
11426 Rockville Pike
Suite 300
Rockville, MD 20852

Laboratory for Atmos. Sci
NASA-Goddard Space Flight
Center
Greenbelt, MD 20771

Commanding Officer
U.S. NAVOCEANCOMCEN
Box 12 FPO
San Francisco, CA 96630-2926

Professor C.-P. Chang
NPS
Monterey, CA 93943

Mr. L. Broadbridge
Regional Director
Bureau of Meteorology
P. O. Box 6070, Hay Street
East Perth,
Western Australia 6000
Australia

Head, Atmos. Sciences Div.
National Science Foundation
1800 G. Street, NW
Washington, DC 20550

Dr. C.-S. Liou
NPS
Monterey, CA 93943

LDCR L. Carr
NPS
Monterey, CA 93943

Mr. J. Arthur
Regional Director
Bureau of Meteorology
P. O. Box 735
Darwin, N. T. 5794
Australia